Plant-mimetic heat pipes for operation with large inertial and gravitational stresses

Abraham Stroock

School of Chemical and Biomolecular Engineering

Kavli Institute at Cornell for Nanoscale Science and Technology

Cornell University

N. Michelle Holbrook and Maciej Zwieniecki

Department of Organismic and Evolutionary Biology

Harvard University

AFOSR - #FA9550-09-1-0188

(B.L. Lee, PM)

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **AUG 2012**	2. REPORT TYPE	3. DATES COVERED **00-00-2012 to 00-00-2012**

4. TITLE AND SUBTITLE **Plant-mimetic heat pipes for operation with large inertial and gravitational stresses**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Cornell University,School of Chemical and Biomolecular Engineering,Kavli Institute at Cornell for Nanoscale Science and Technology,Ithaca,NY,14853**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at the 2nd Multifunctional Materials for Defense Workshop in conjunction with the 2012 Annual Grantees'/Contractors' Meeting for AFOSR Program on Mechanics of Multifunctional Materials & Microsystems Held 30 July - 3 August 2012 in Arlington, VA. Sponsored by AFRL, AFOSR, ARO, NRL, ONR, and ARL. U.S. Government or Federal Rights License

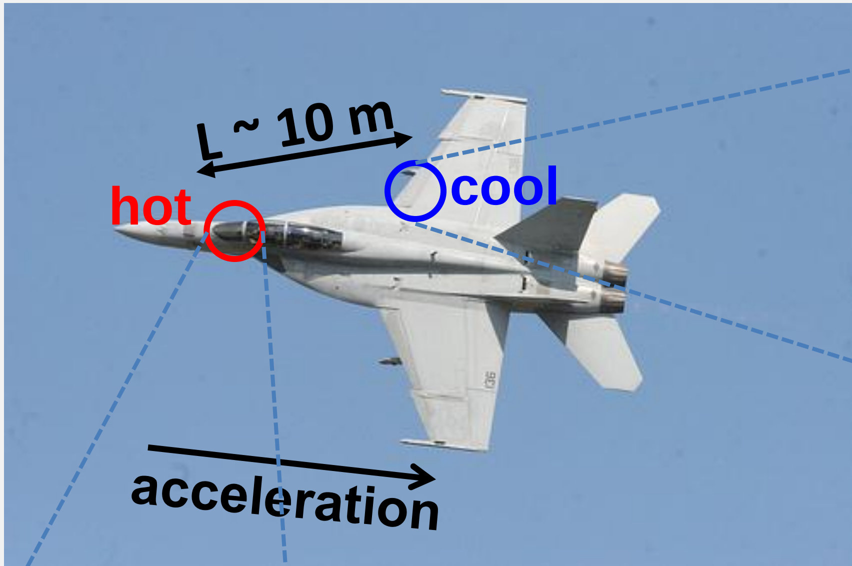
14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**43**	

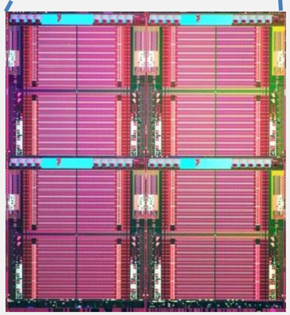
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Problem – *efficient heat transfer*



temperature:

$T_{sink} \lesssim 40\ °C$



heat flux:

$J \rightarrow 100\ W/cm^2$

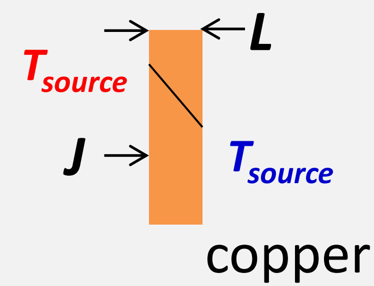
temperature:

$T_{source} \lesssim 100\ °C$

$\Delta T_{min} = 60\ °C$

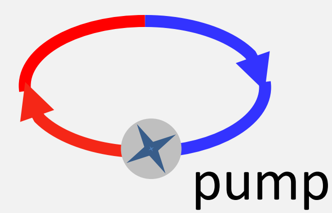
Conduction:

$$L = \frac{k\Delta T}{J} = 2.4\ \text{cm}$$



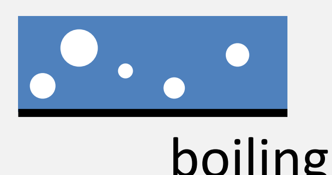
Convection:

$$Q = \frac{J}{\rho C_p \Delta T} = 0.4\ \frac{\text{mL/s}}{\text{cm}^2}$$

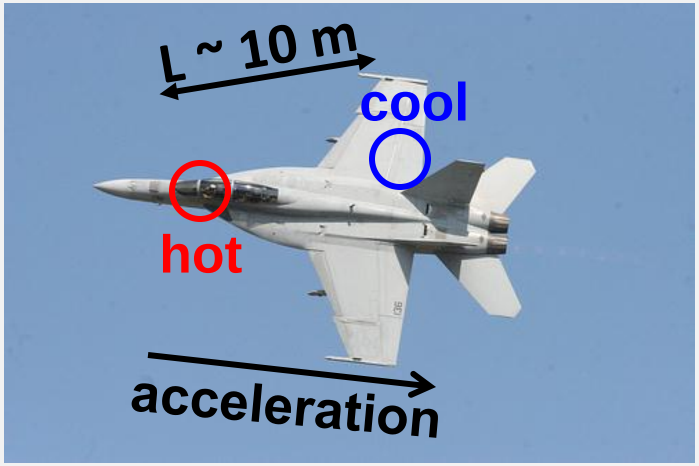


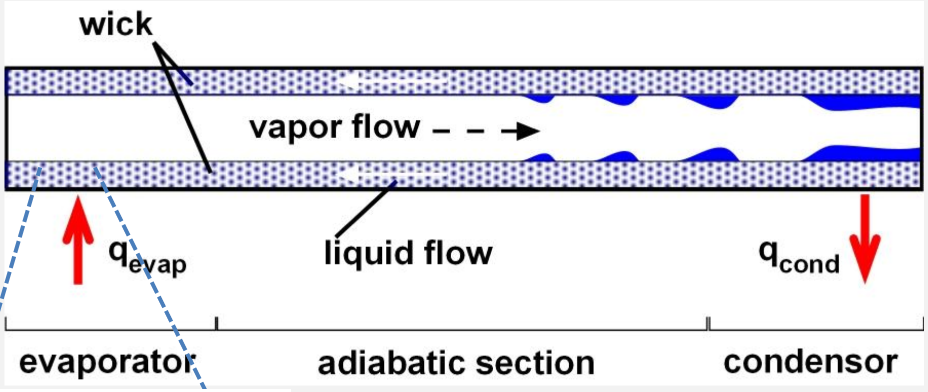
Phase change:

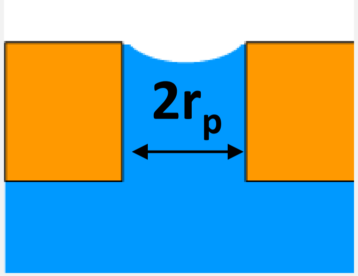
$$Q = \frac{J}{\rho\lambda} = 0.04\ \frac{\text{mL/s}}{\text{cm}^2}$$

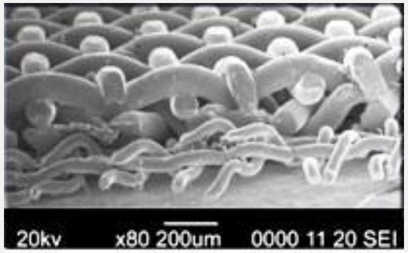


Heat pipes – closed loop phase change









www.microloops.com

Advantages

- autonomous (no pump)
- self-contained
- near-isothermal operation

Limitations

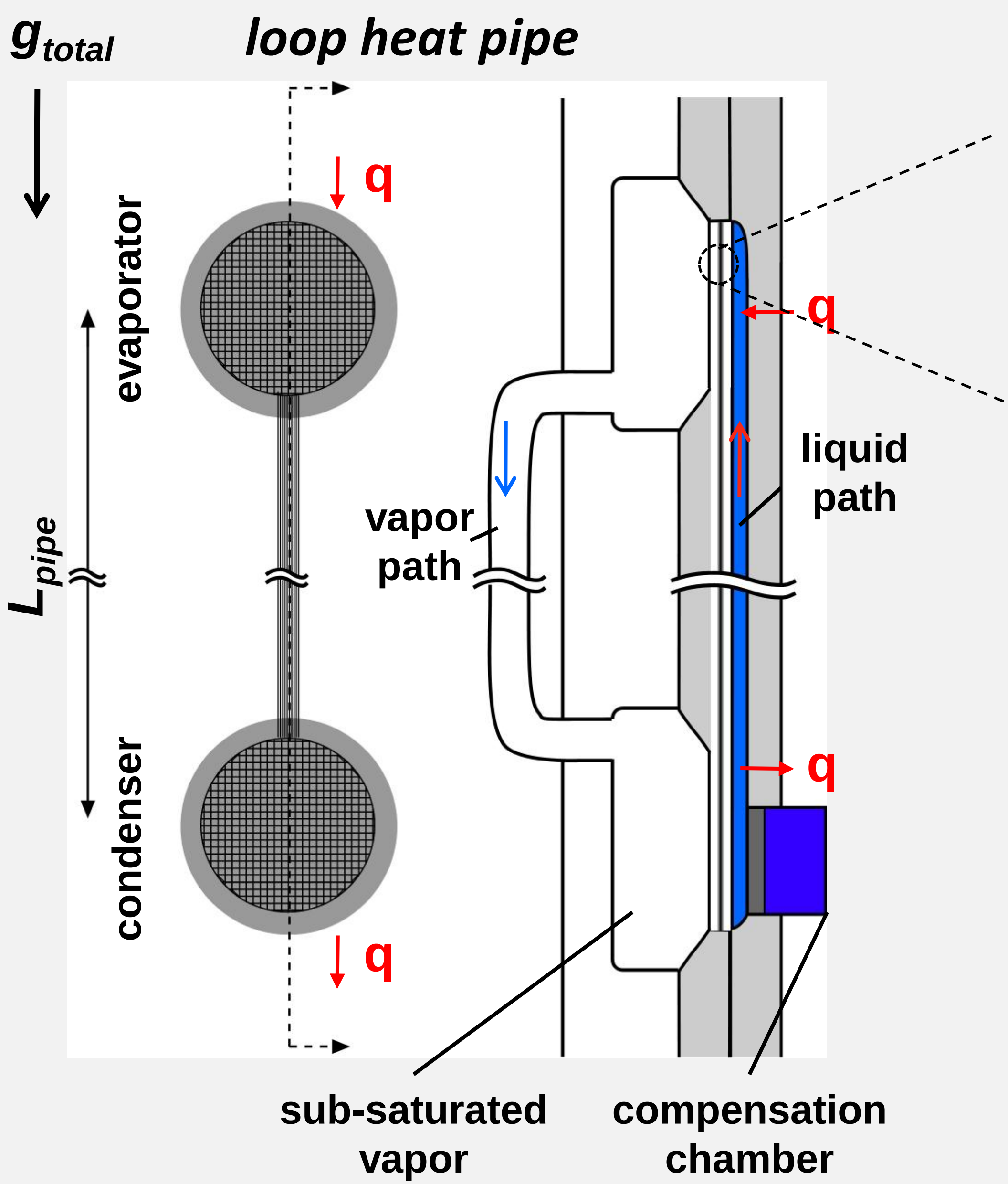
- capillary limit
  - $\Rightarrow$ short (~1 m), low load ($\leq$ 1 g)
- entrainment limit
  - $\Rightarrow$ limited heat flow

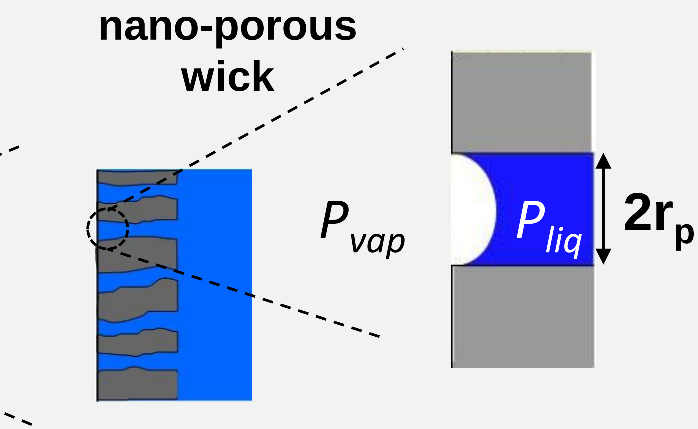
$$r_p \geq 1\,\mu\text{m} \qquad \Delta P \leq \frac{2\gamma}{r_p} \leq 1\,\text{bar}$$

<u>Goal</u>: Efficient heat transfer

- over long distances (10 m)
- with adverse gravitational and inertial loads (up to 10 g)

Opportunity *– large stresses from small pores*





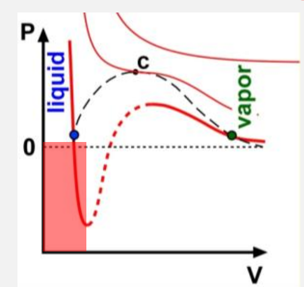
$$r_p < 10\,\mathrm{nm}$$

$$P_{vap} - P_{liq} = \frac{2\gamma}{r_p} >> 1\,\mathrm{bar}$$

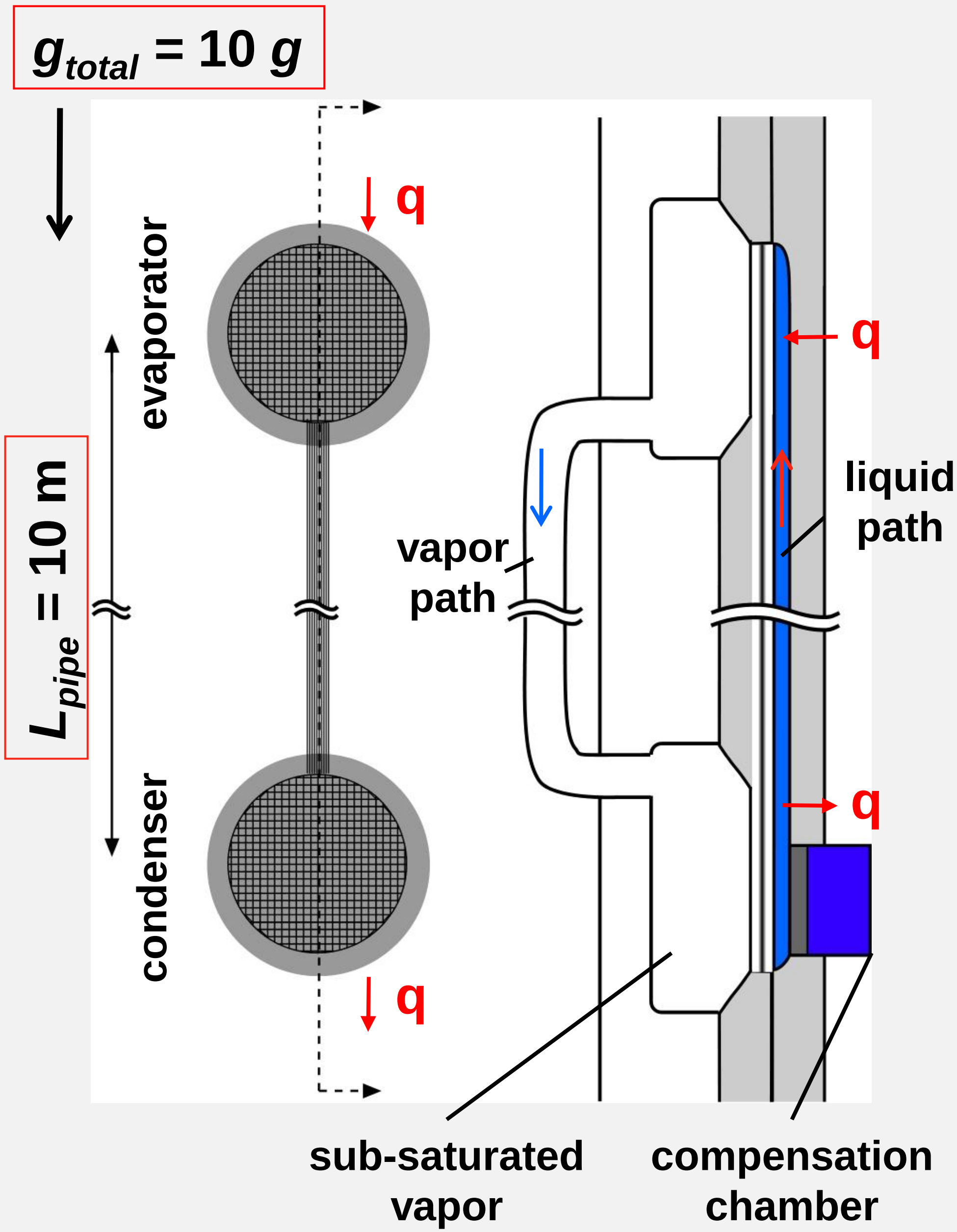
$$\Rightarrow P_{liq} = P_{vap} - \frac{2\gamma}{r_p} << 0$$

$\Rightarrow$ **Negative pressure**

$\Rightarrow$ **Metastable (superheated)**

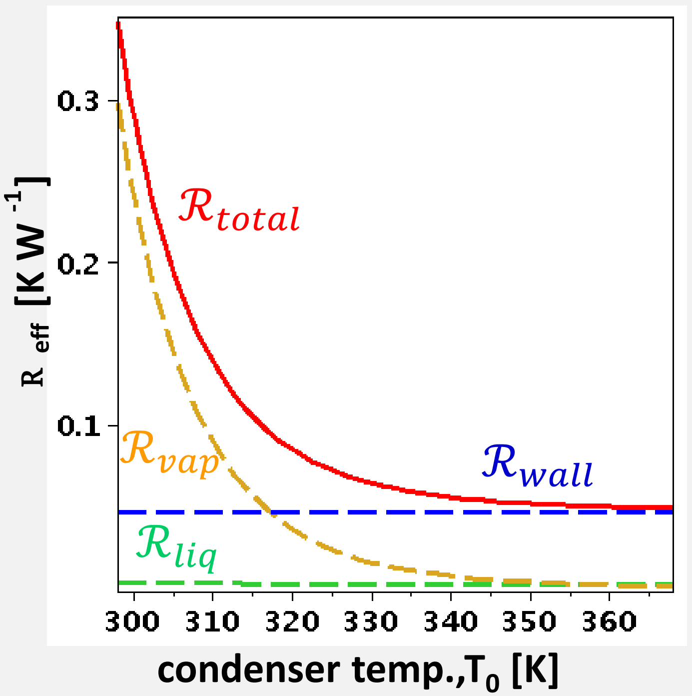


Opportunity – large stresses from small pores



Effective Thermal Resistance:

$$\mathcal{R}_{total} = \mathcal{R}_{liq} + \mathcal{R}_{vap} + \mathcal{R}_{wall}$$



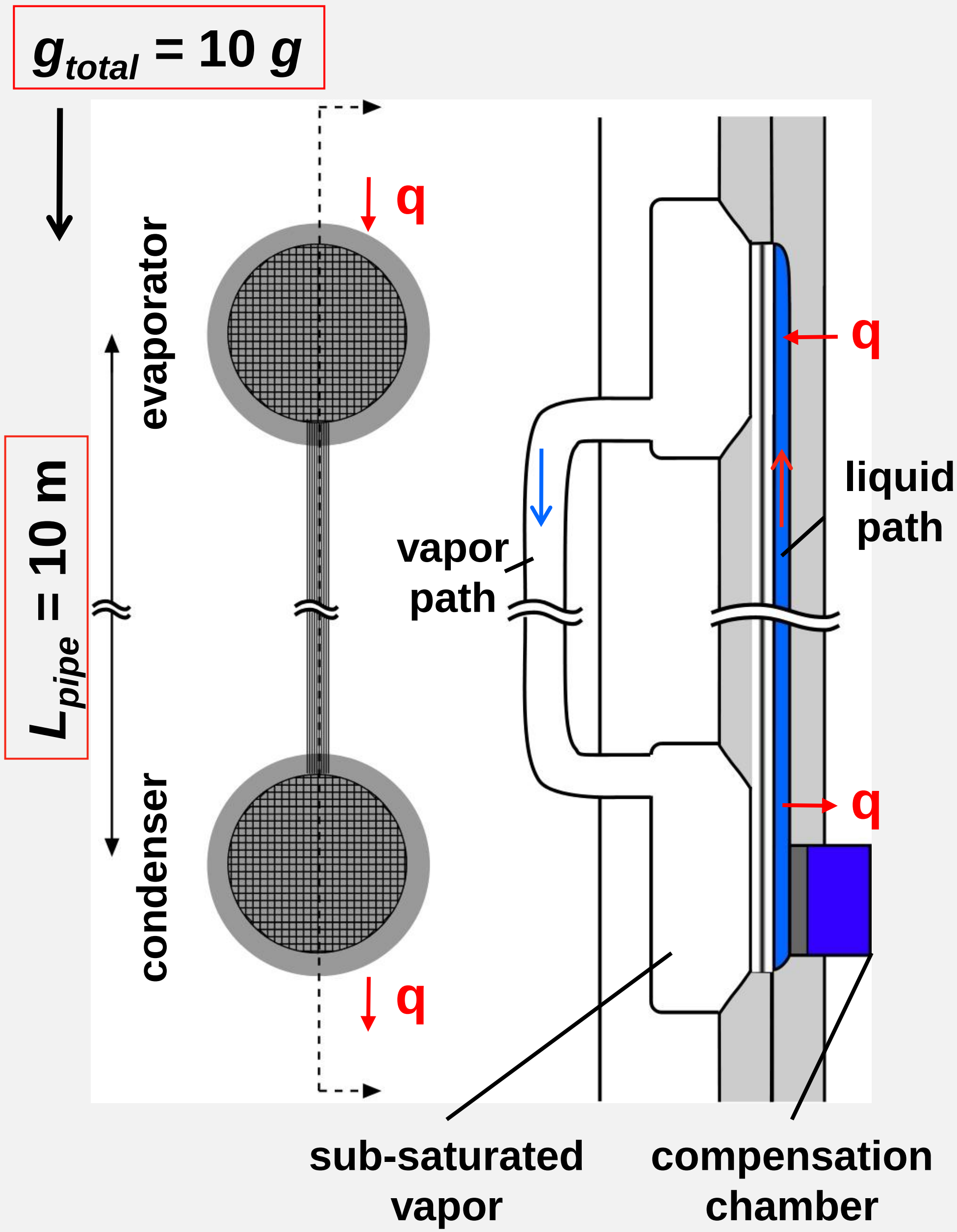
- **Impact of viscous and inertial stresses negligible.**

$\Rightarrow R_{total} \sim R_{wall}$

$\Rightarrow$ **total resistance ~ 3 mm of copper**

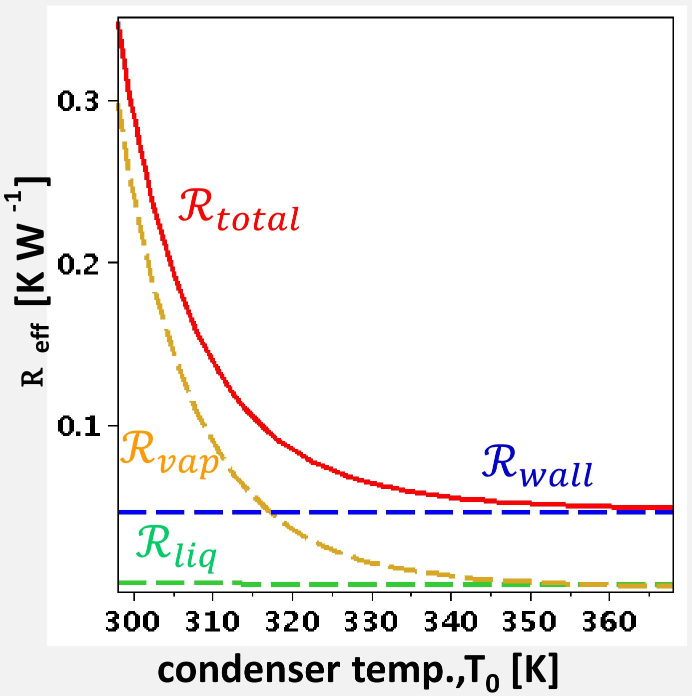
(Chen et al., submitted, 2012)

Challenge – large stresses from small pores



Effective Thermal Resistance:

$$\mathcal{R}_{total} = \mathcal{R}_{liq} + \mathcal{R}_{vap} + \mathcal{R}_{wall}$$

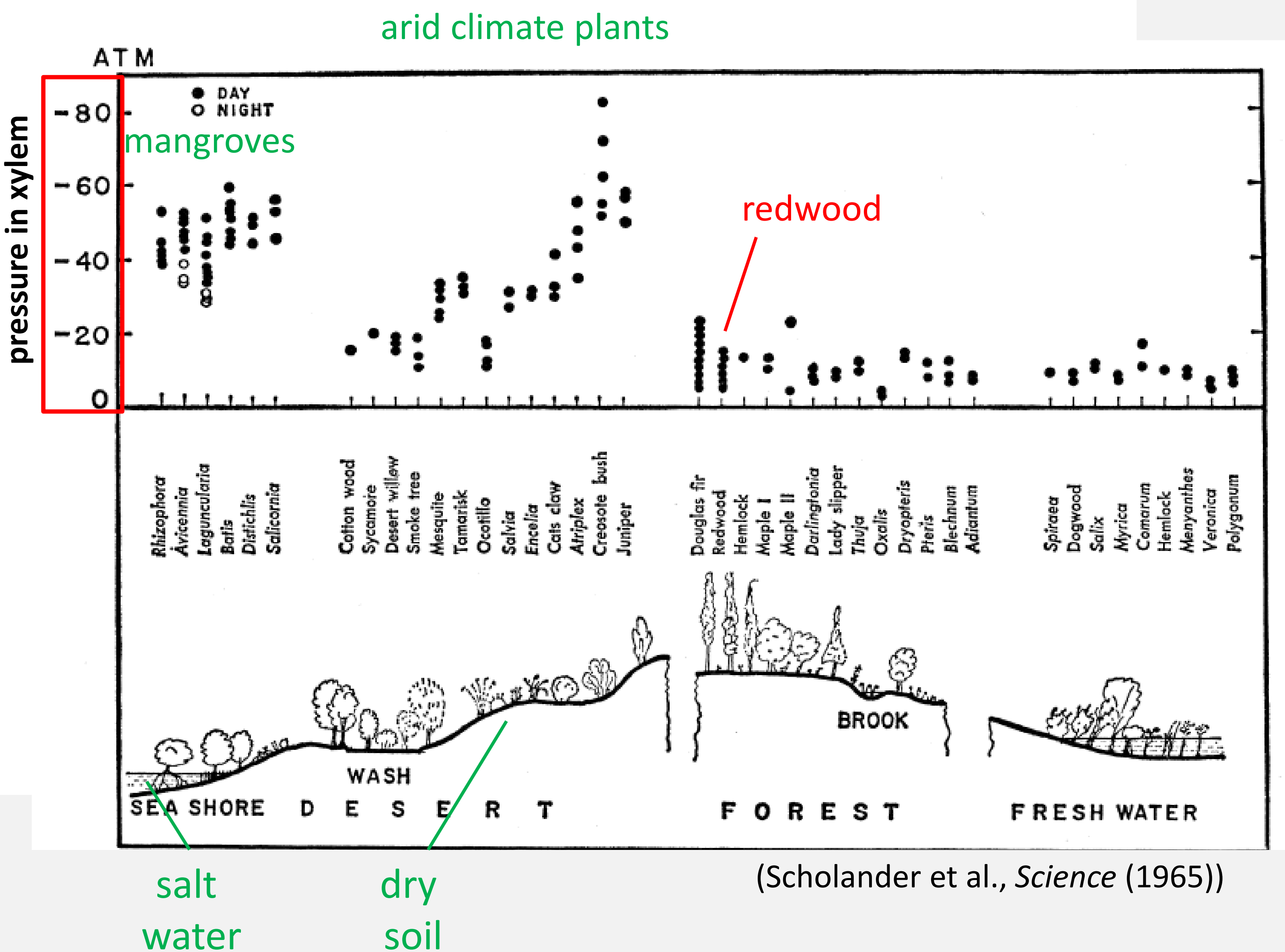


- P_{liq} **~ -20 bars** for q = 10 W/cm^2
- additional -1 bar per W/cm^2

$\Rightarrow$ **must manage metastability**

(Chen et al., submitted, 2012)

Challenge – but plants do it every day…



(Scholander et al., *Science* (1965))

Synthetic trees - *negative pressure wicks*

"soil": (liquid)

$a_s = 1$

$P = P_0$

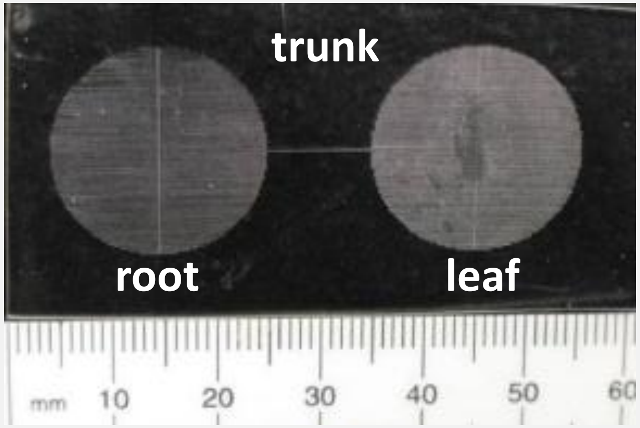
$T = 25°$

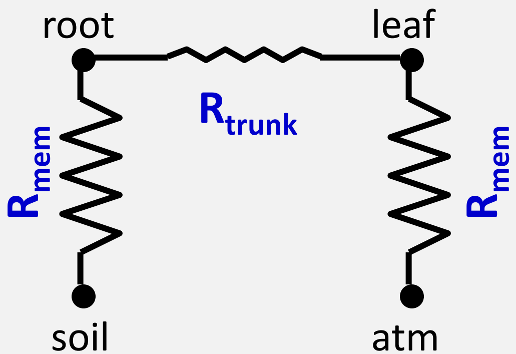
"atm": (vapor)

$a_a = 0.75$

$P = P_0$

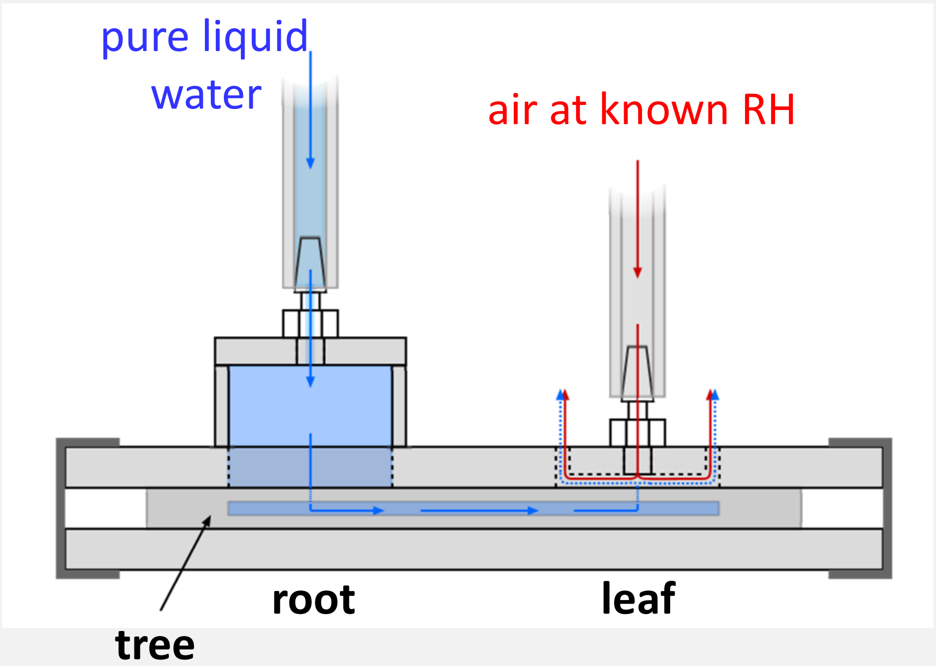
$T = 25°$





Ψ_{soil} = 0 bar

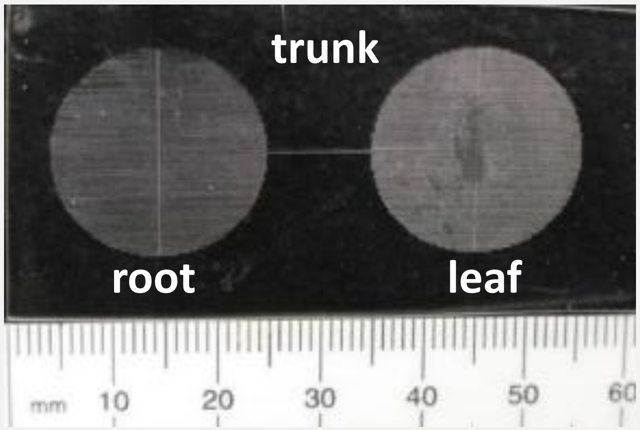
Ψ_{atm} = -380 bar

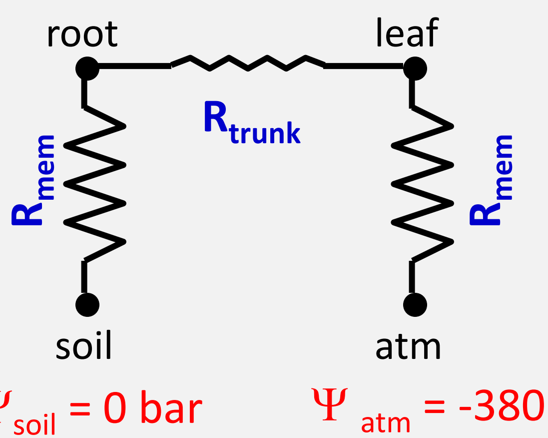


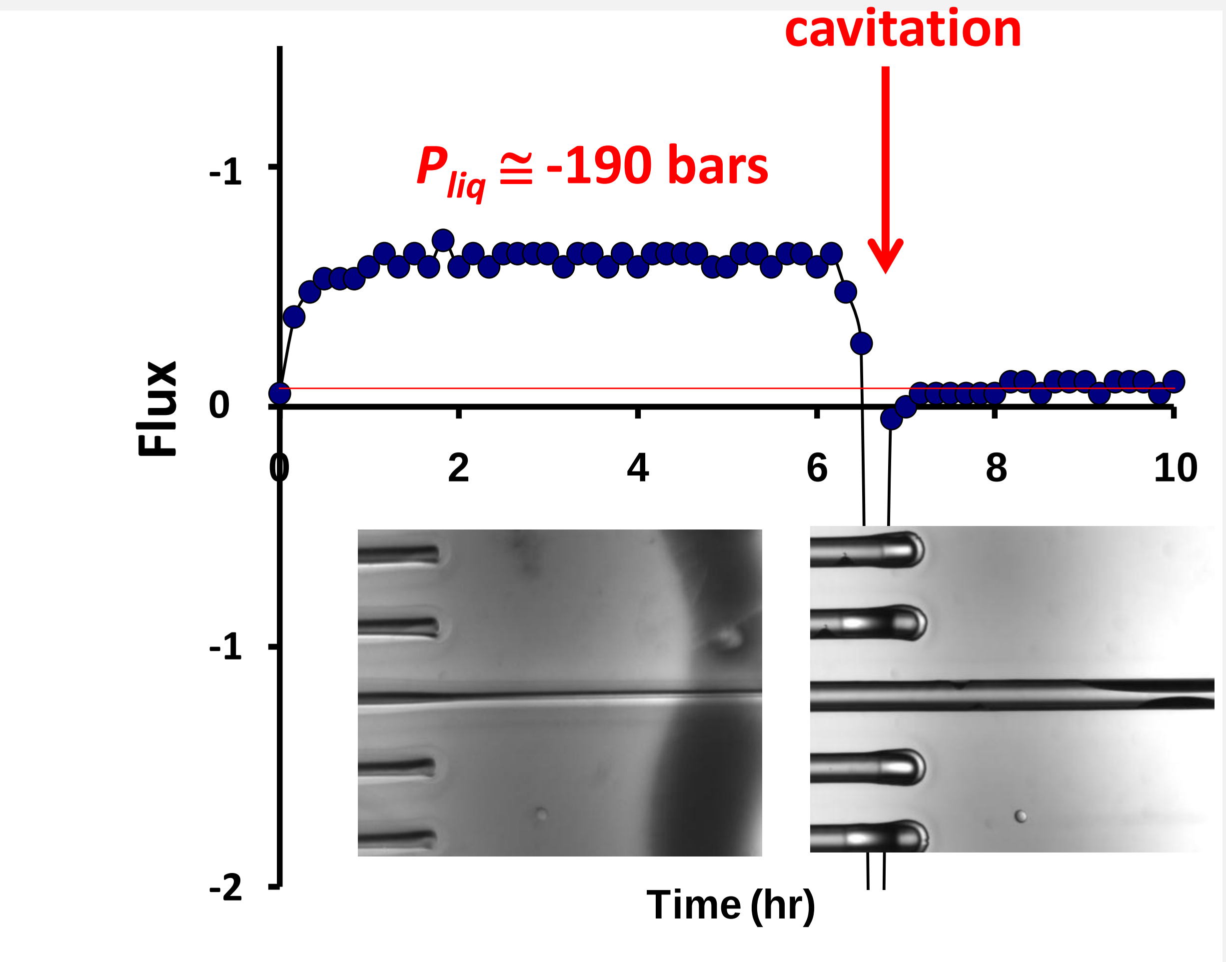
(Wheeler & Stroock, Nature, 2008)

Synthetic trees - negative pressure wicks

"soil": (liquid)	"atm": (vapor)
$a_s = 1$	$a_a = 0.75$
$P = P_0$	$P = P_0$
$T = 25°$	$T = 25°$

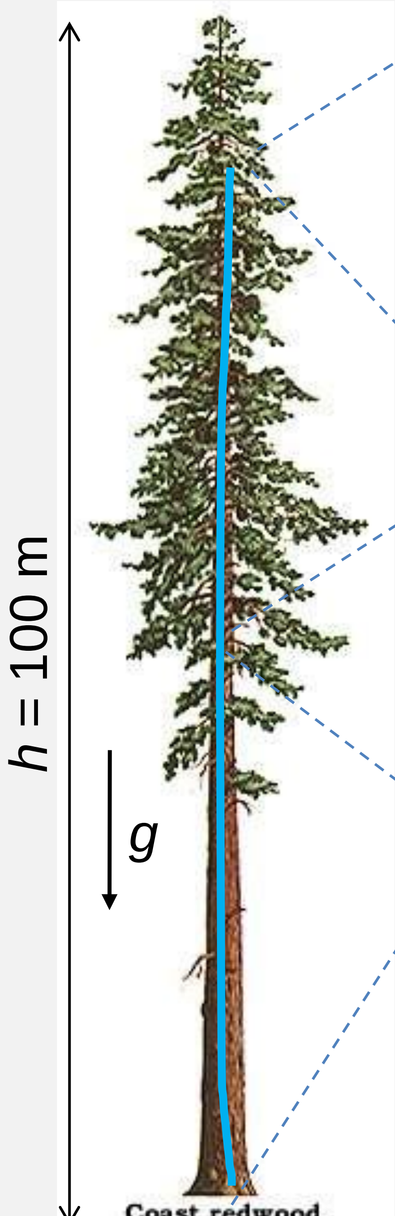




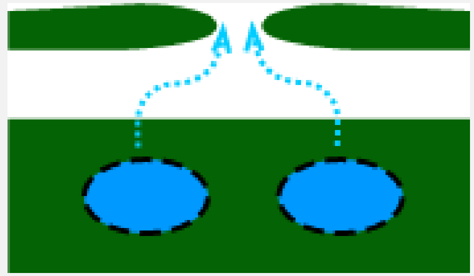


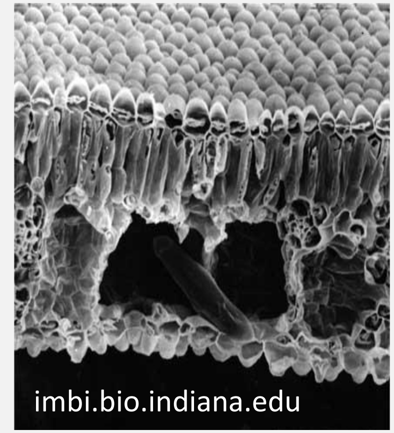
- catastrophic failure
- mechanical collapse
- low flux (large membrane resistance)

Managing tension

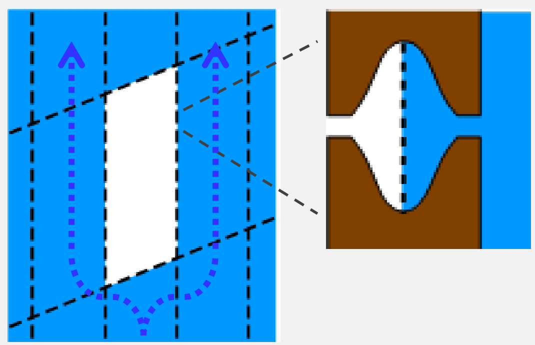


needles/leaves

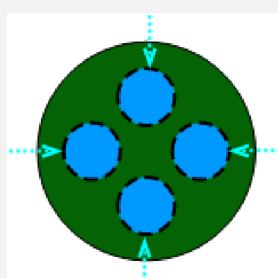


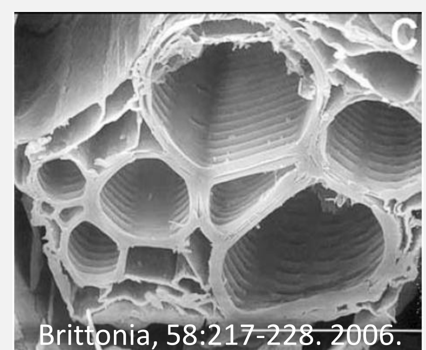


xylem vessels

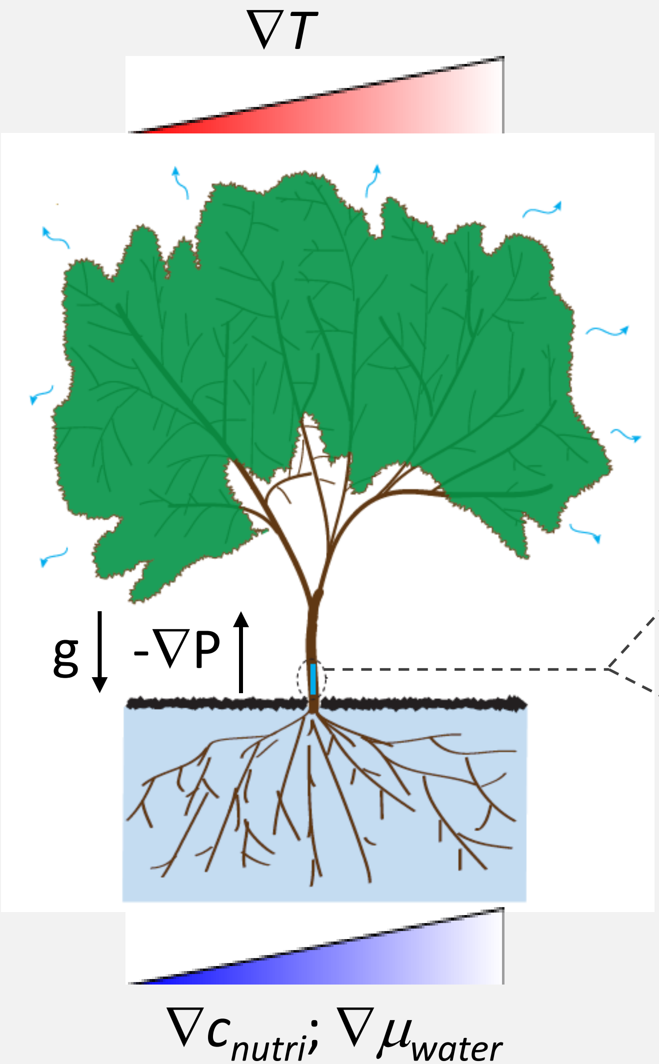


roots



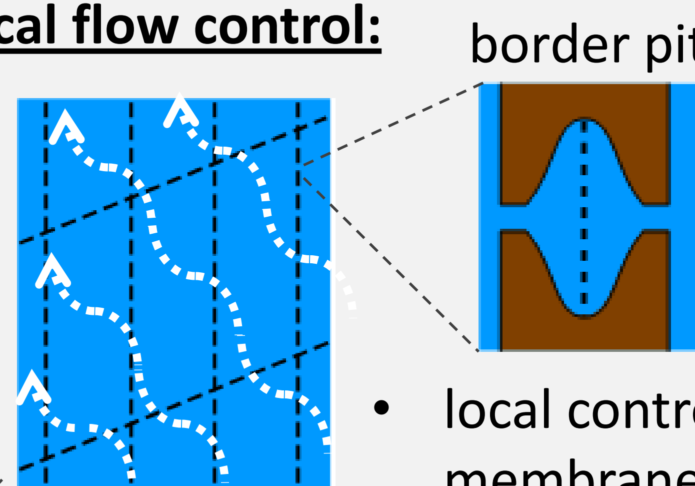


Managing tension – *autonomic functions*



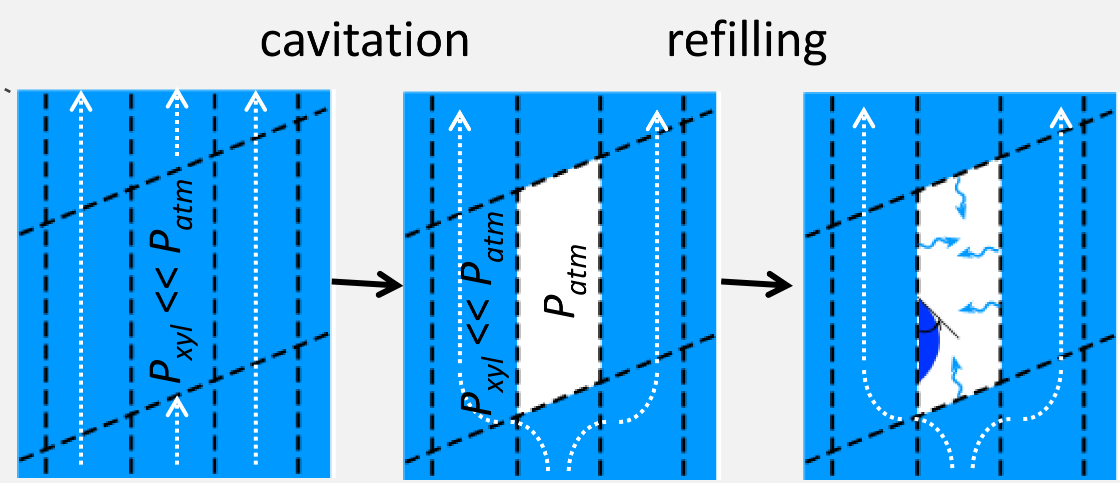
"xylem is dead wood"

1. local flow control:



- local control of membrane resistance

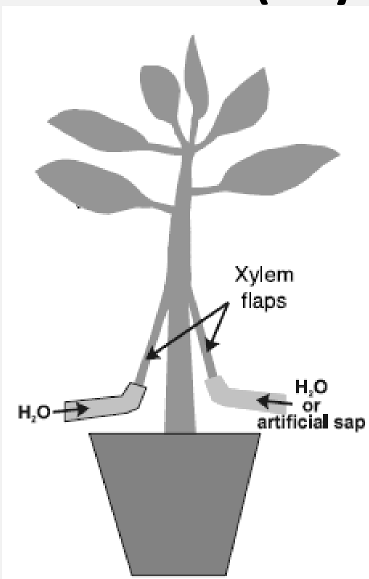
2. recovery after cavitation:



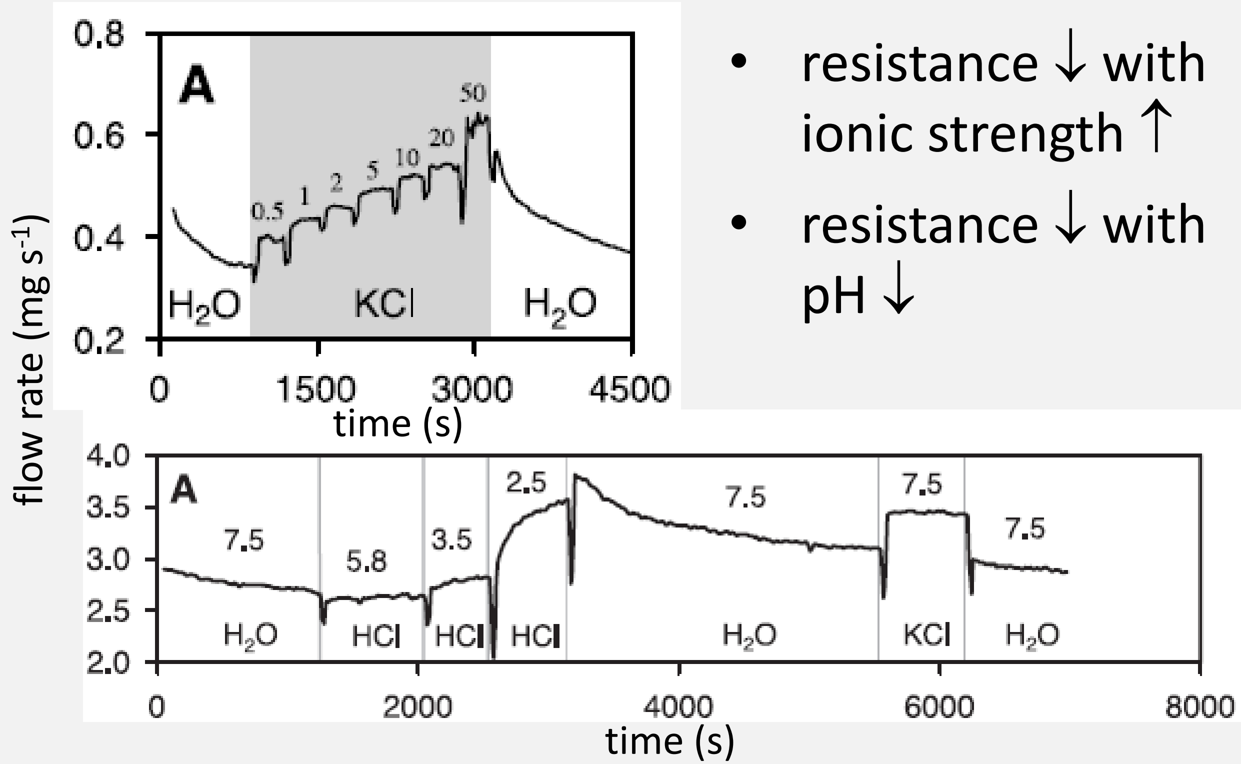
(*isolated failure*)

1. Flow control – experiments

lauris nobilis (bay tree)

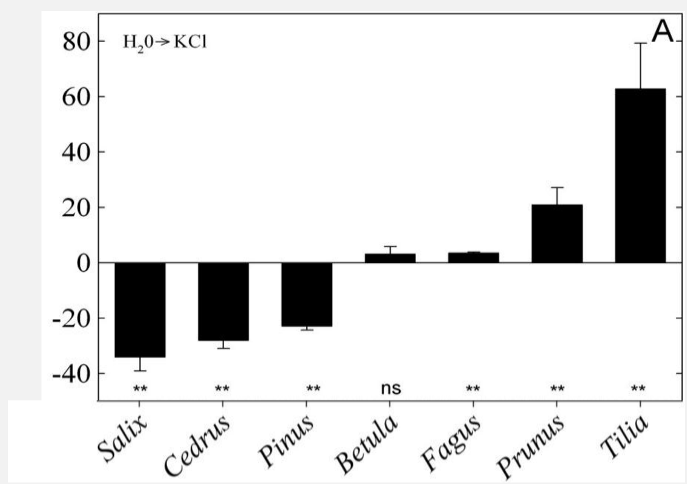


(Zwieniecki et al., Science, 2001)



- resistance ↓ with ionic strength ↑
- resistance ↓ with pH ↓

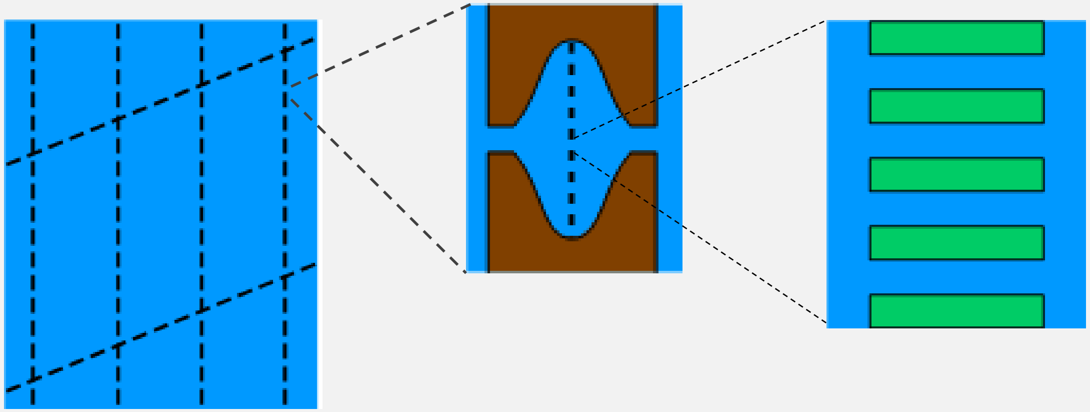
various species



- sign and magnitude depend on species

(Cochard et al., J. Exp. Bot., 2009)

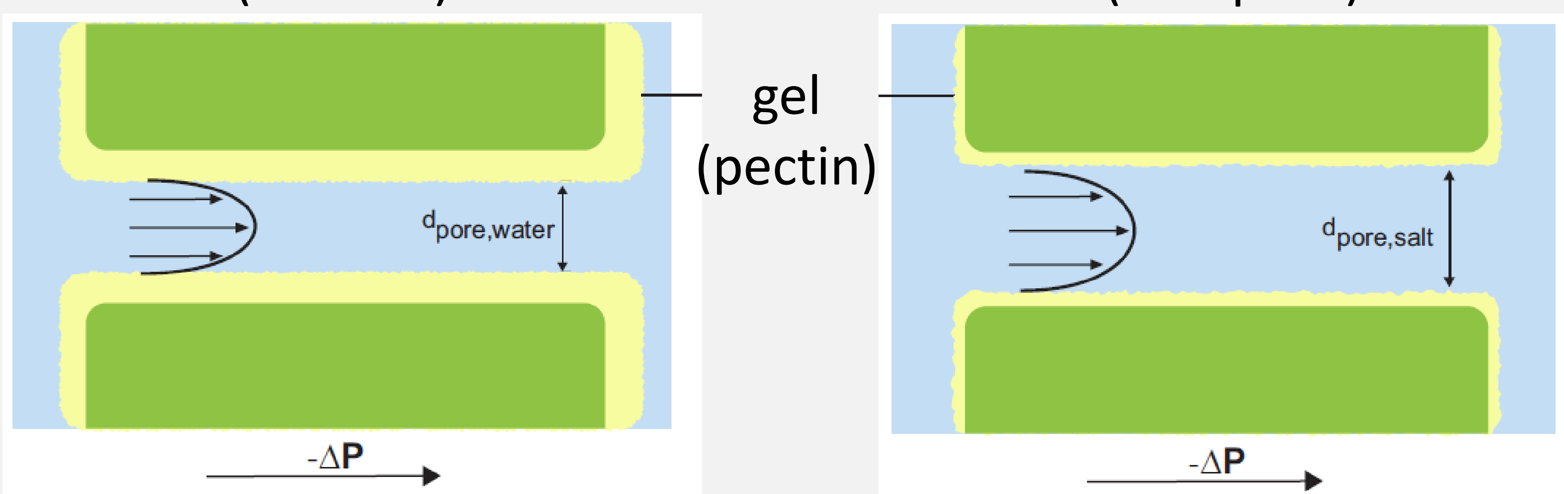
1. Flow control – mechanisms



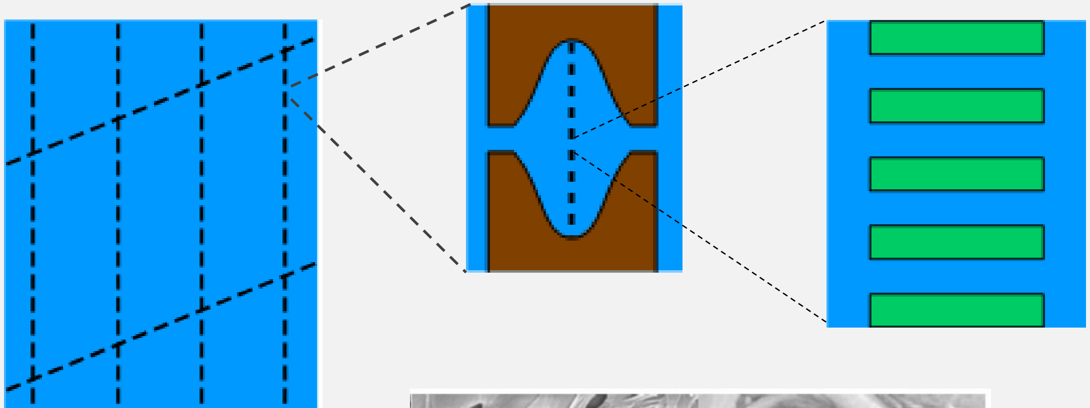
Hydrogel:

low ionic strength/neutral pH (swollen)

high ionic strength/low pH (collapsed)

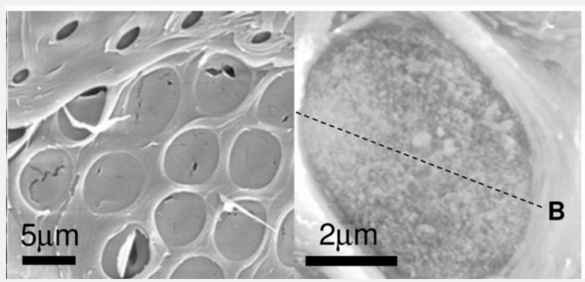


1. Flow control – mechanisms



Hydrogel:

SEM

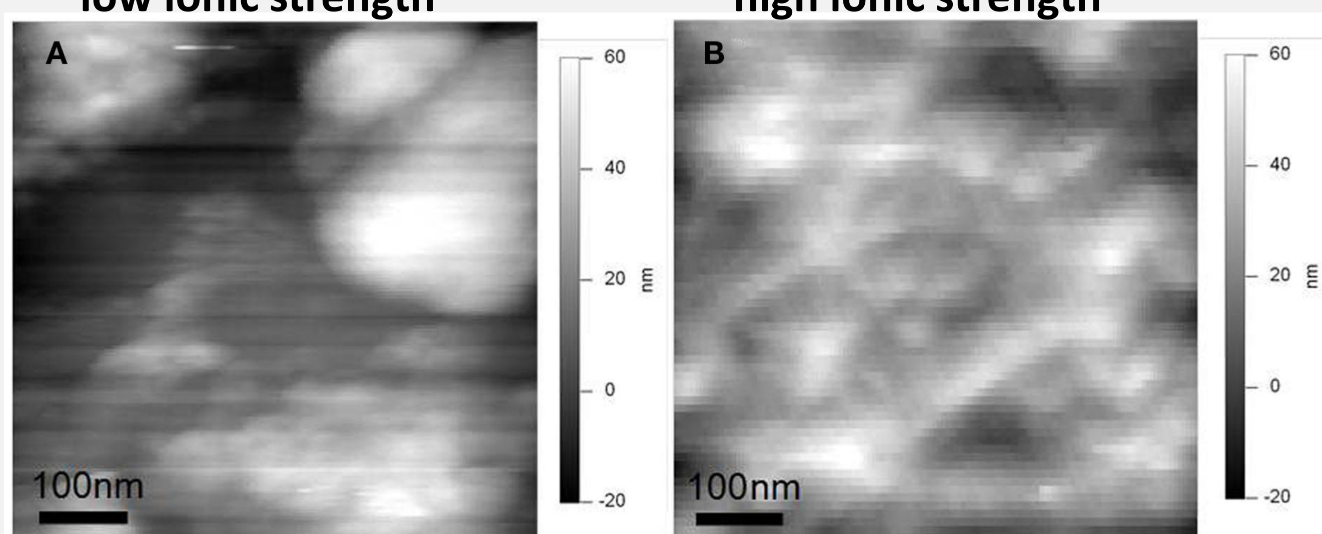


(Lee, Holbrook & Zwieniecki, Front. Plant Sci., 2012)

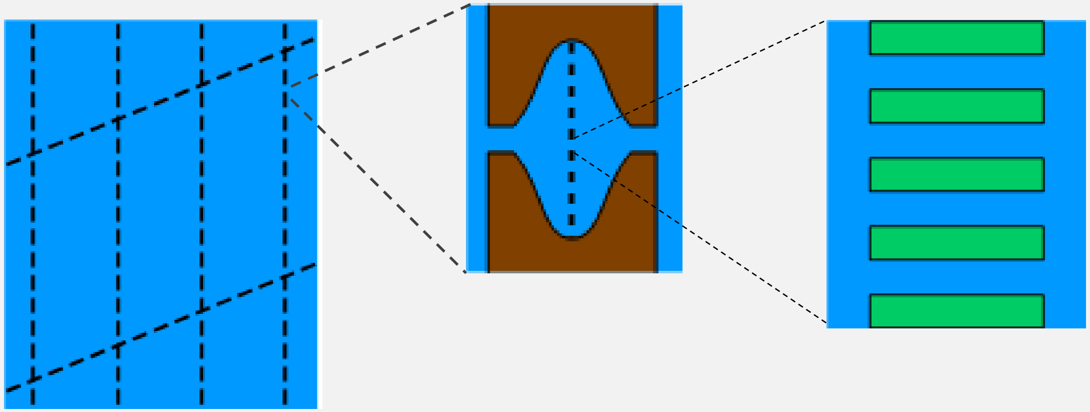
high ionic strength/low pH
(collapsed)

AFM

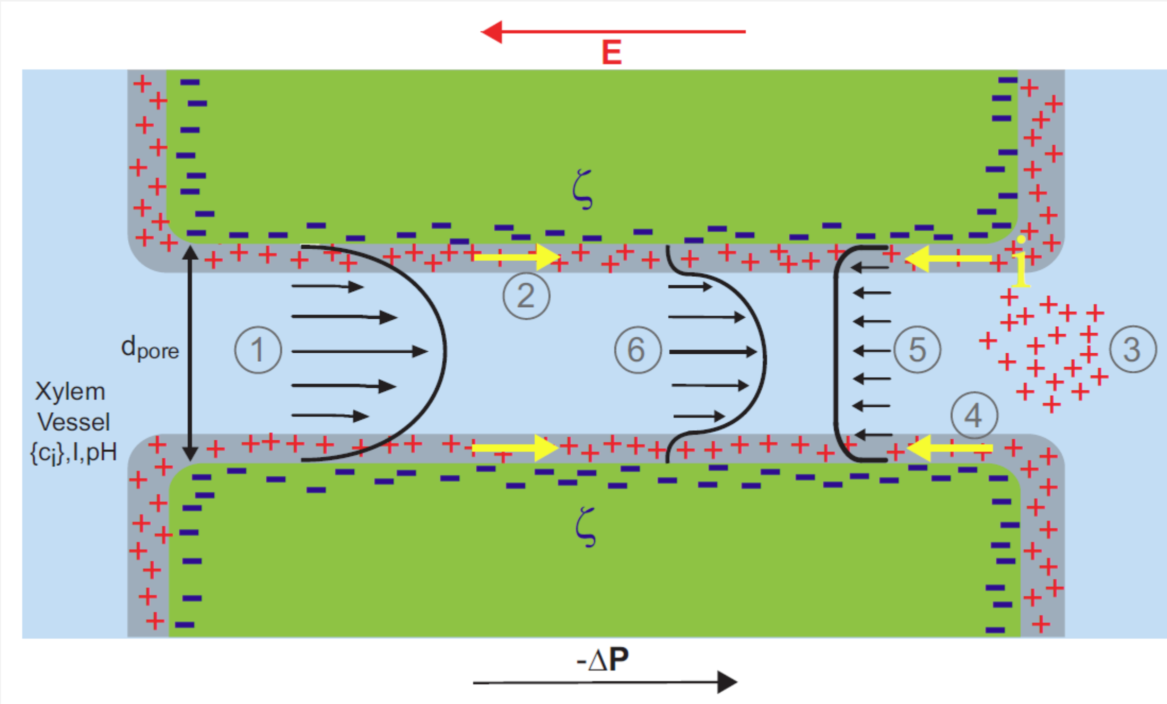
low ionic strength **high ionic strength**



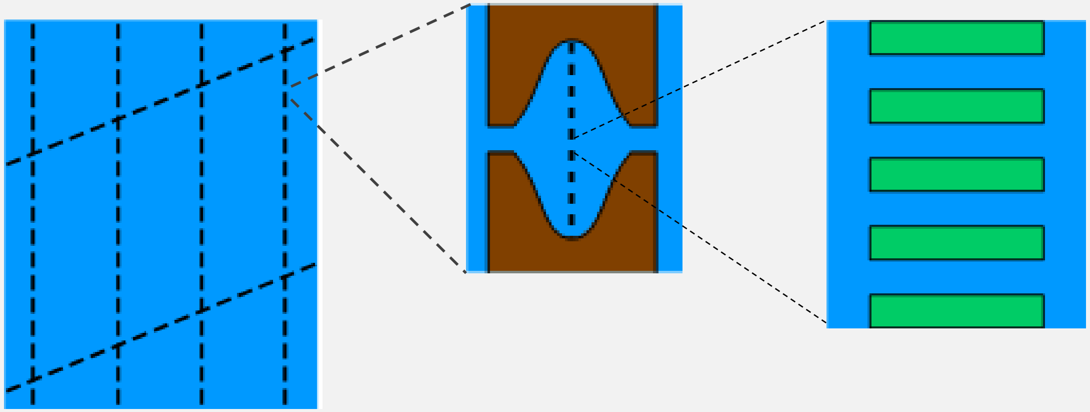
1. Flow control – mechanisms

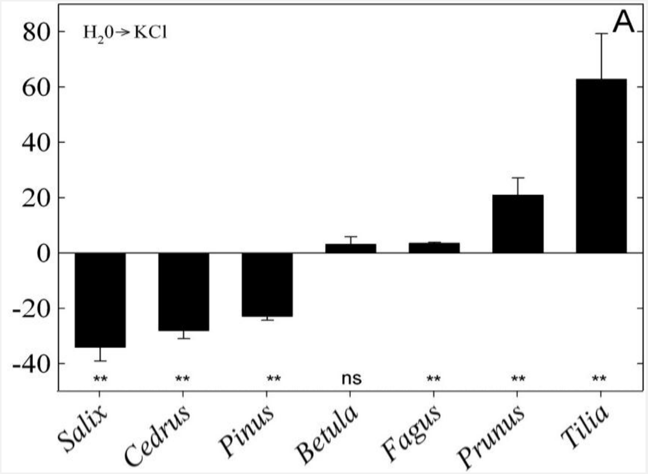


Electroviscous effect:



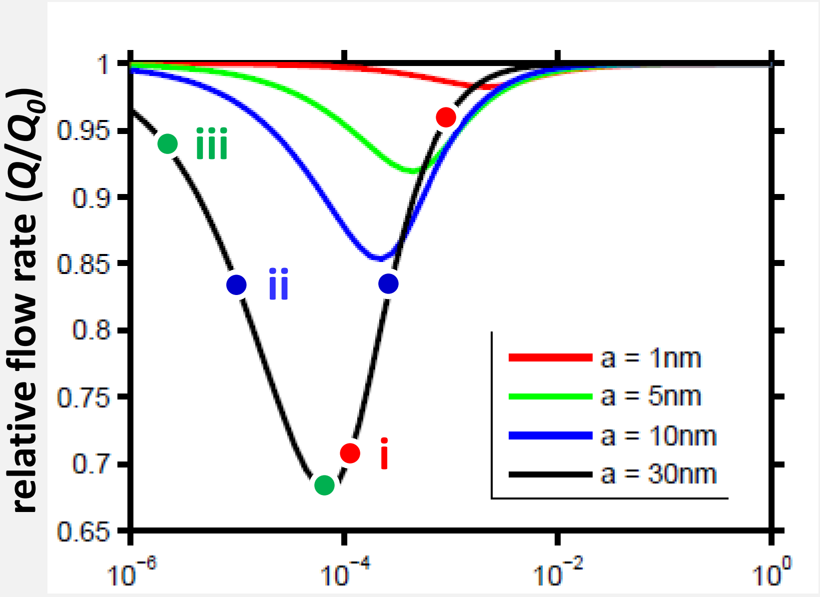
1. Flow control – mechanisms





(Cochard et al., J. Exp. Bot., 2009)

Electroviscous effect:



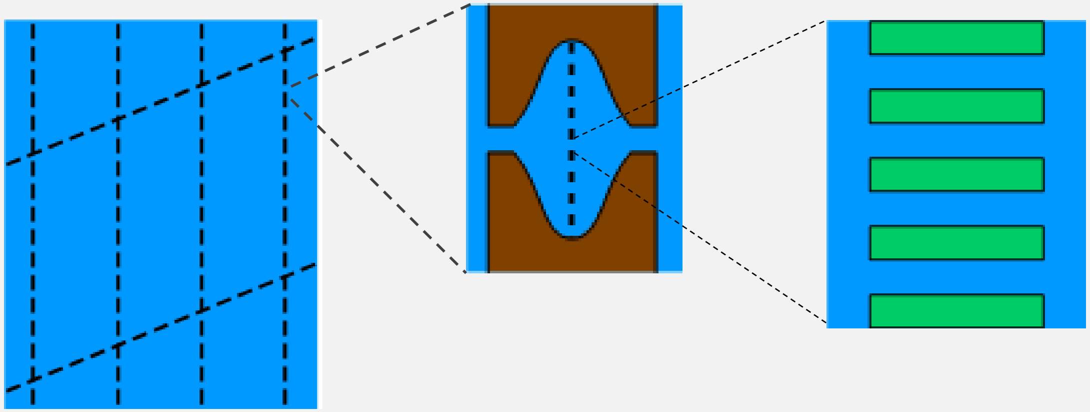
i. positive

ii. neutral

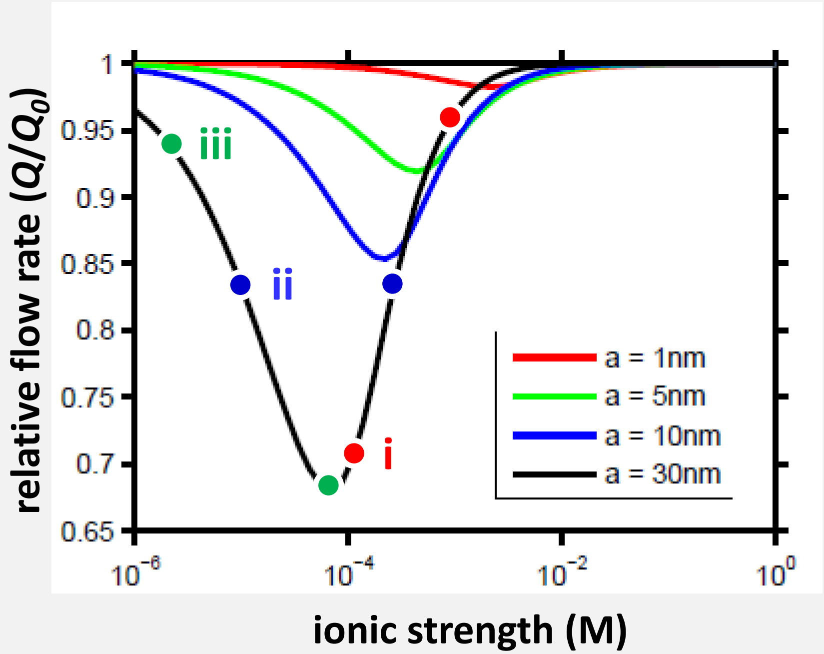
iii. negative

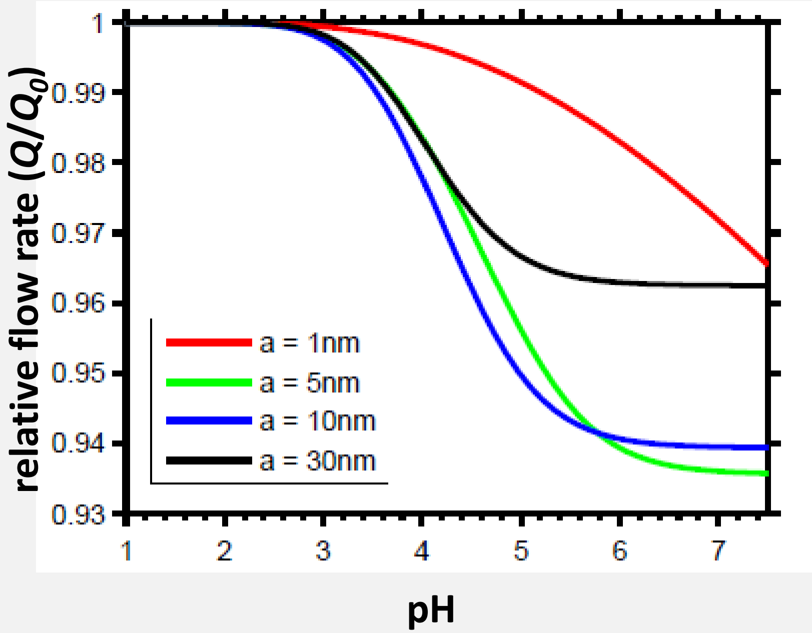
(Santiago et al., in preparation, 2012)

1. Flow control – *mechanisms*



Electroviscous effect:

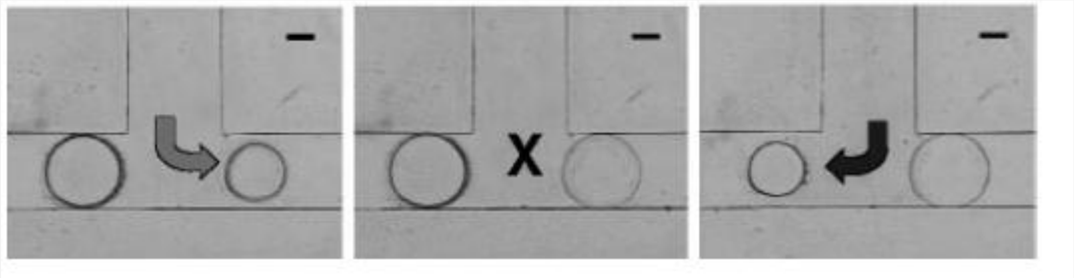




(Santiago et al., in preparation, 2012)

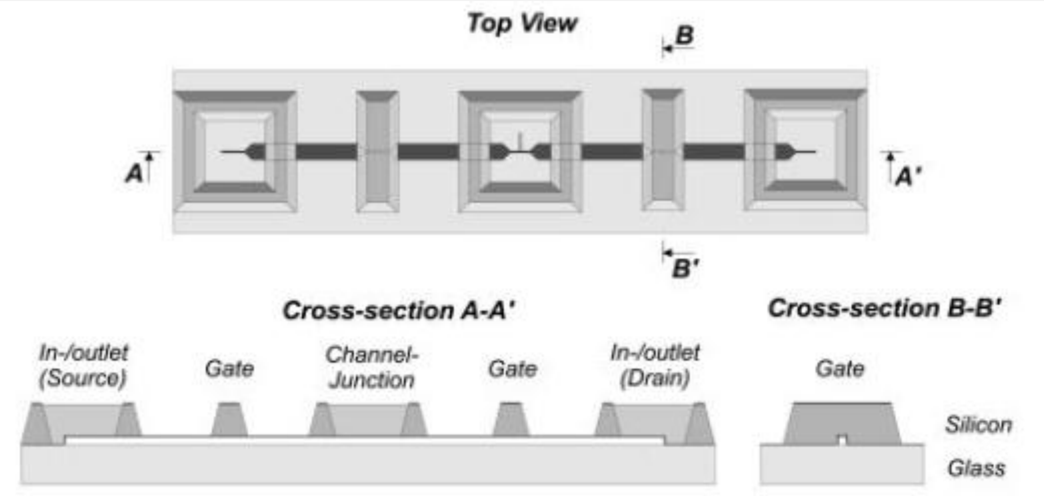
1. Flow control – *precedent*

Hydrogel:

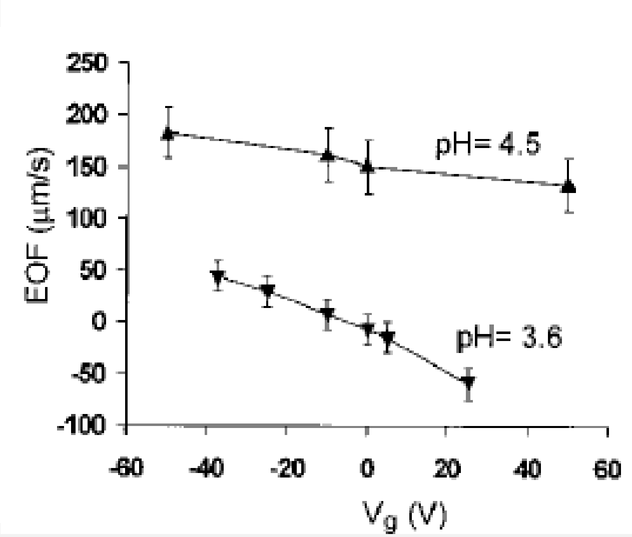


(Beebe et al., Nature, 2000)

Electroviscous effect:



"FlowFET"

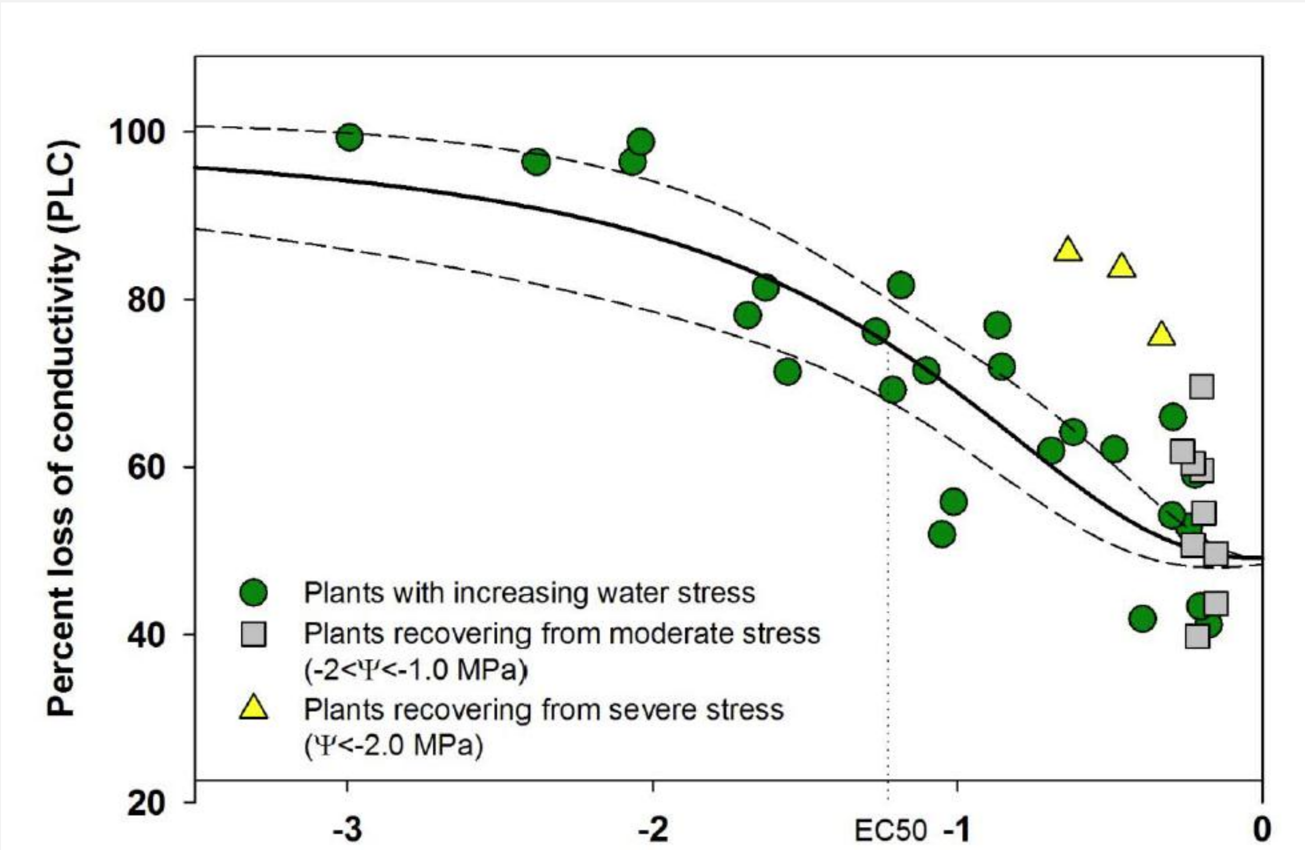


(Schasfoort et al., Science, 1999)

2. Refilling – experiments

Populus nigra (black poplar)

increased cavitation



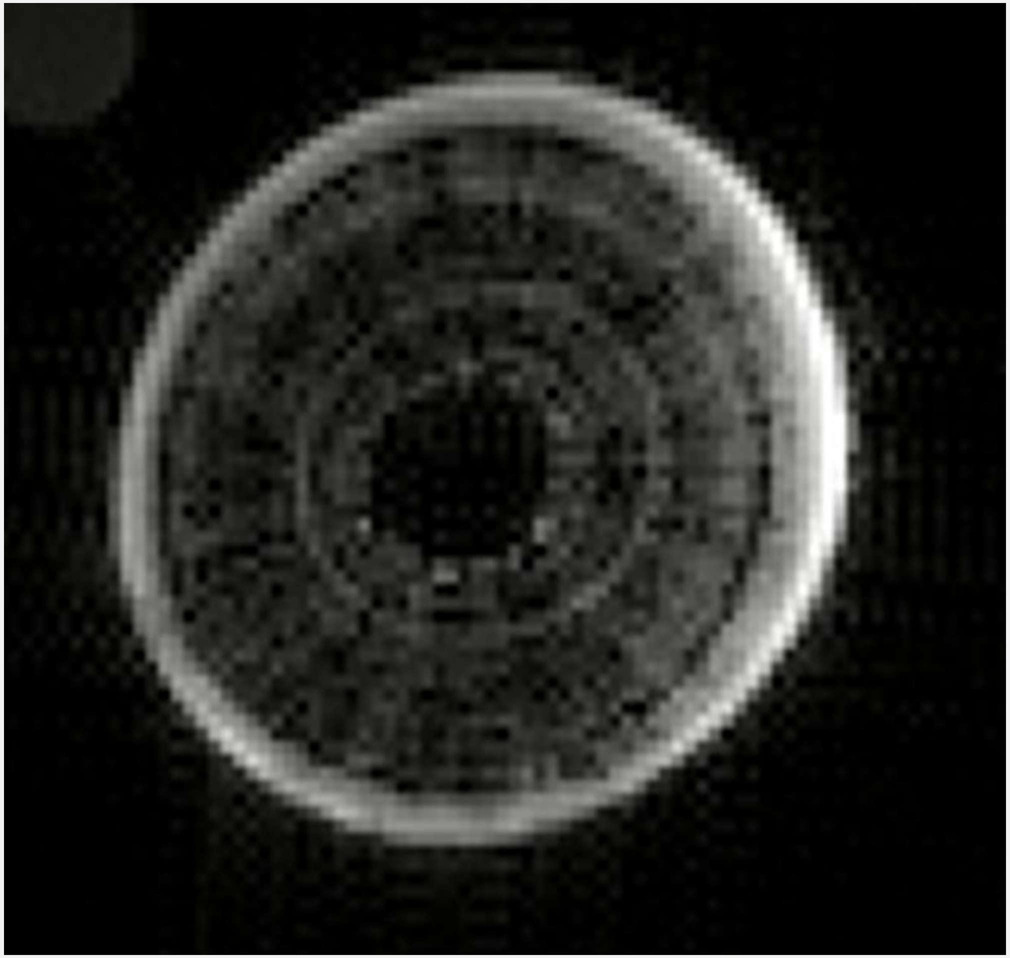
pressure in xylem (MPa = 10 bar)

(Secchi and Zwieniecki, 2012)

2. Refilling – experiments

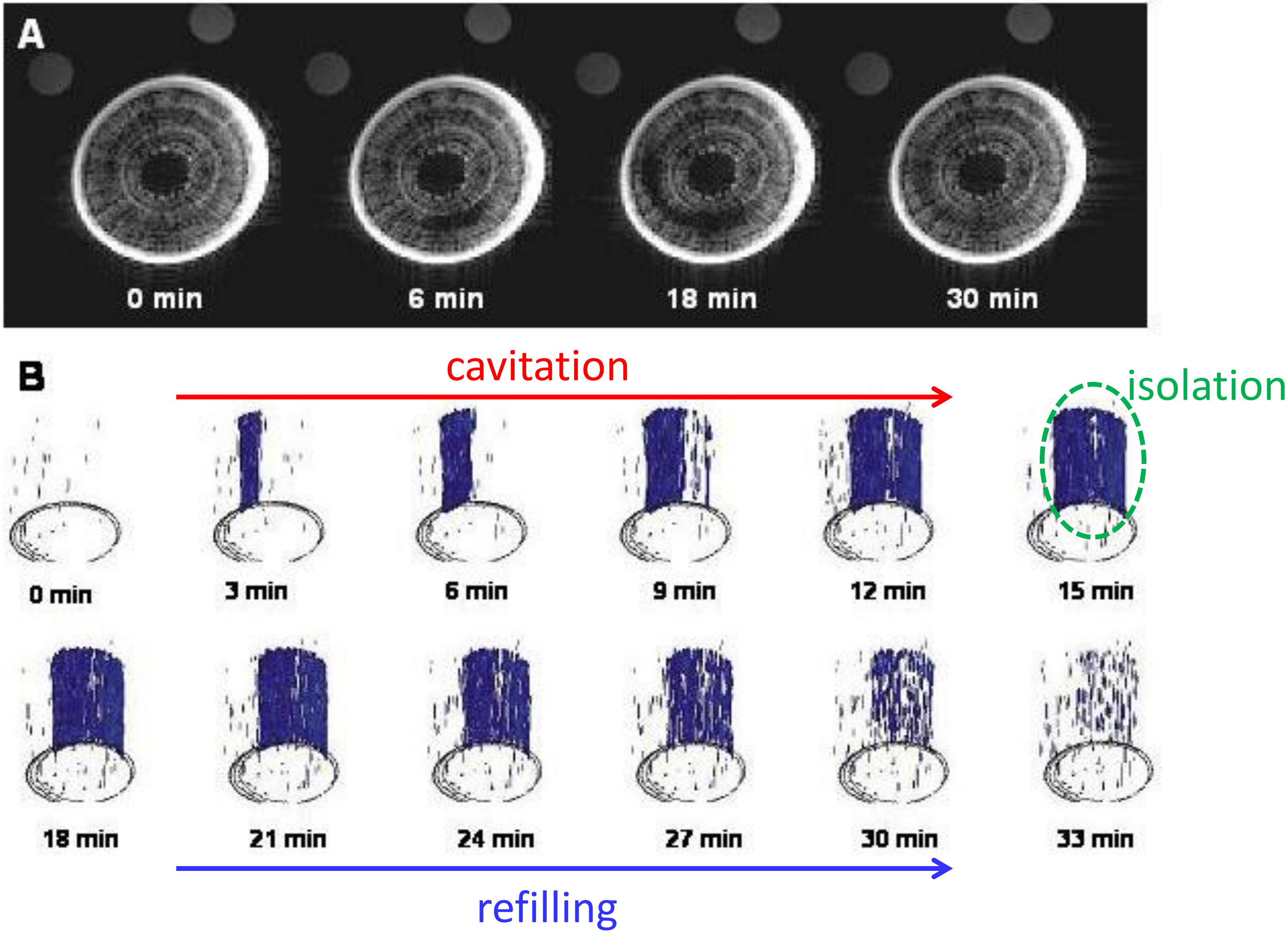
***Acer rubrum* (red maple); $P_{vessels}$ = -5 bars**

MRI
(30 minutes)



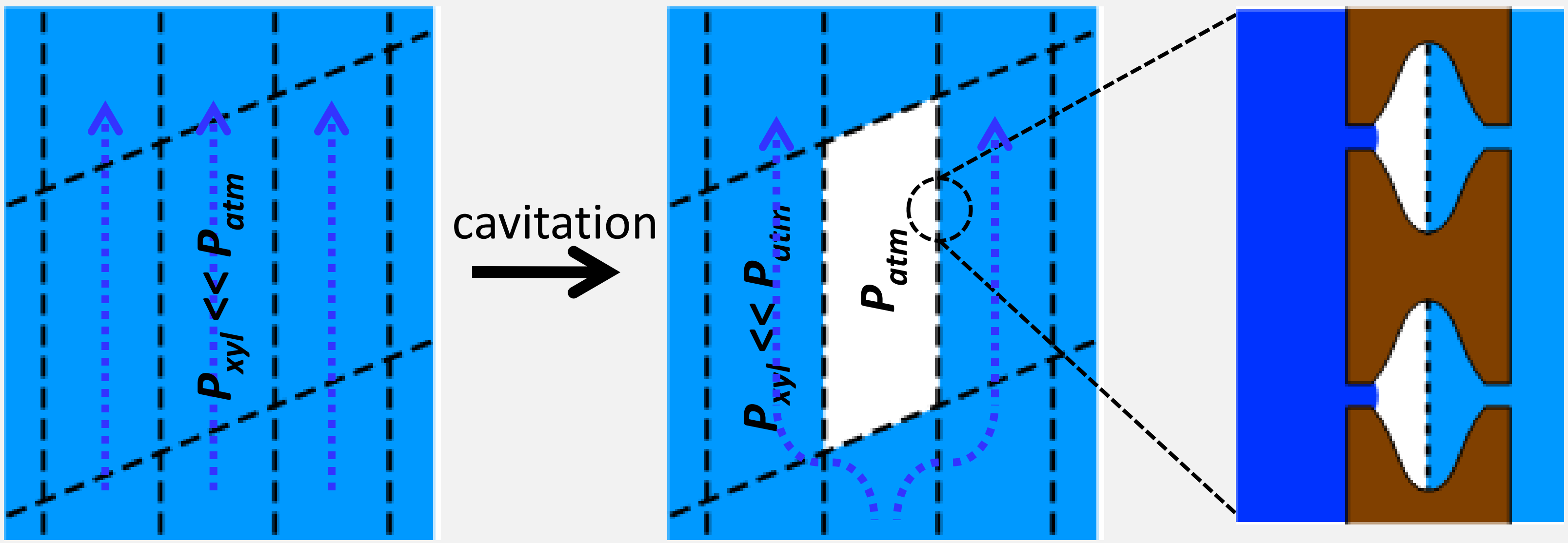
(Zwieniecki, Melcher, Ahrens & Holbrook, in revisions, 2012)

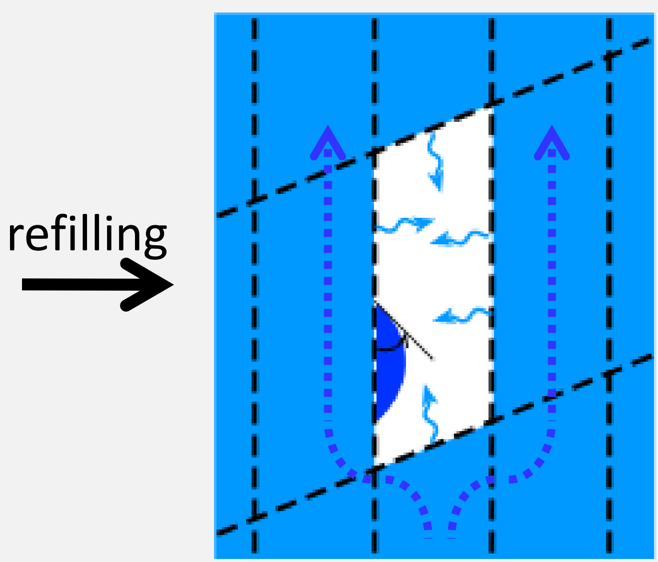
2. Refilling – experiments



(Zwieniecki, Melcher, Ahrens & Holbrook, in revisions, 2012)

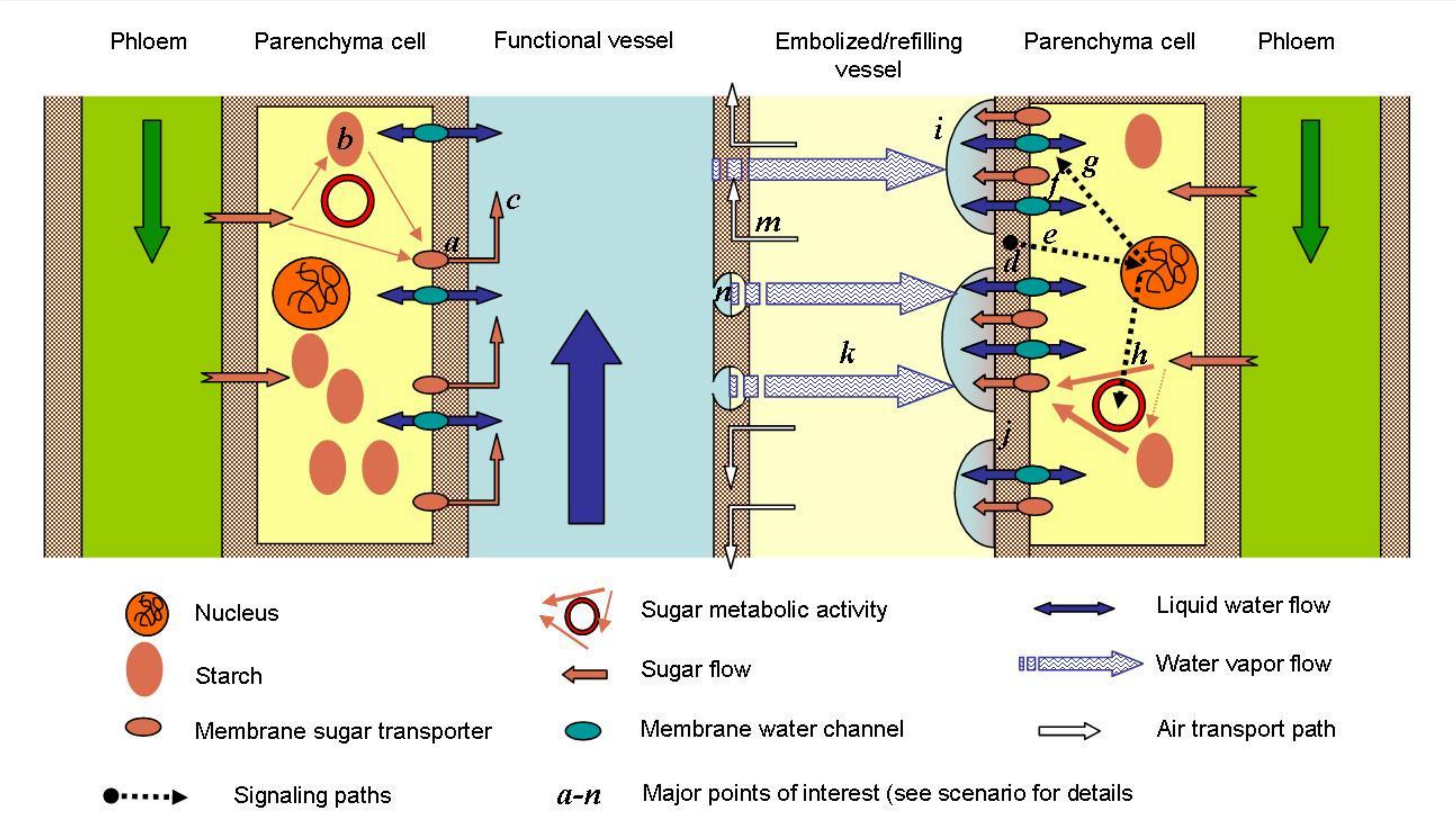
2. Refilling – mechanism?





- **trigger?**
- **transport?**
- **energy?**

2. Refilling – mechanism?

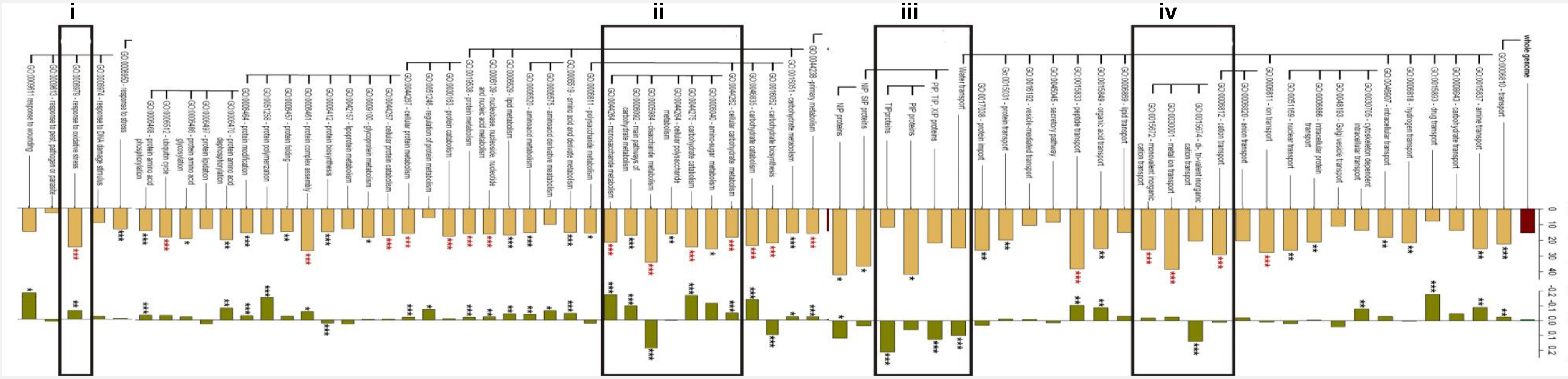


(Zwieniecki & Holbrook, Trends in Plant Sciences, 2009)

2. Refilling – molecular mechanisms

Differential gene expression after induced embolization

Populus trichocarpa (black cottonwood)



- ~9,000 genes differentially expressed after embolization
- Clues to biochemical and biophysical mechanisms

i,ii) pore proteins ⇒ **active and passive transport mechanisms**

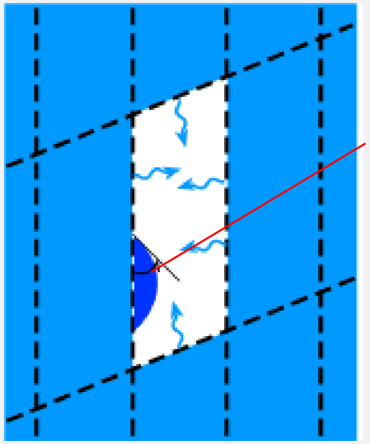
iii) carbohydrate metabolism ⇒ **source of deployable energy**

iv) down regulation of genes for oxidative stress ⇒ **possible trigger**

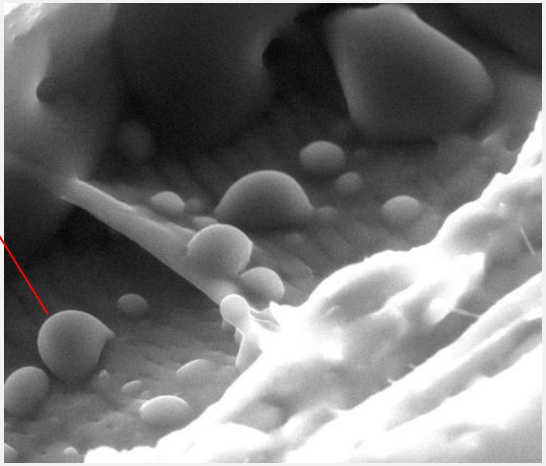
(Secchi et al., Plant Physio, 2011)

2. Refilling – biophysical mechanisms

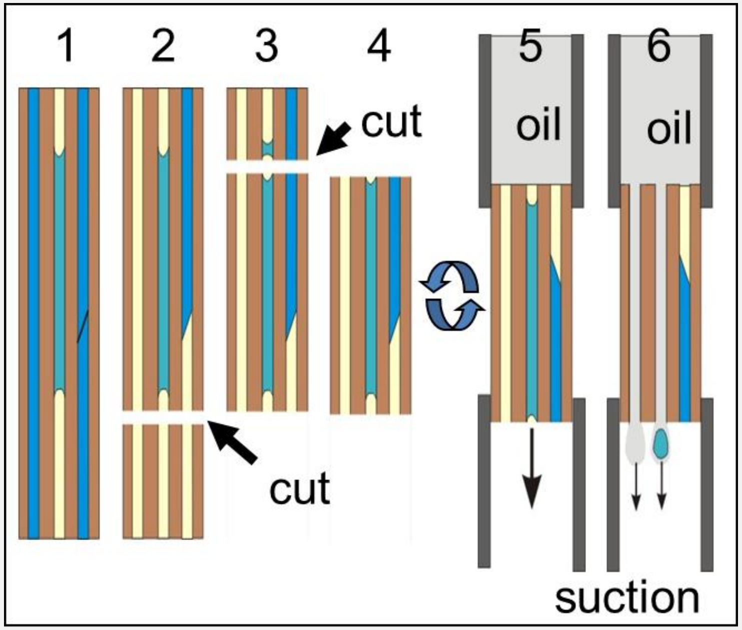
Driving force for refilling?:



what's in this water?



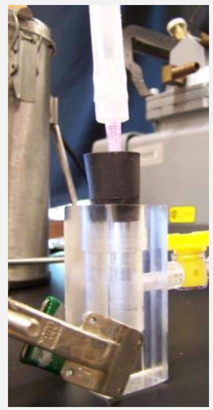
$$\text{activity} = \; a \leq exp\left(\frac{\bar{v}\left(P_{xyl} - P_0\right)}{RT}\right)$$

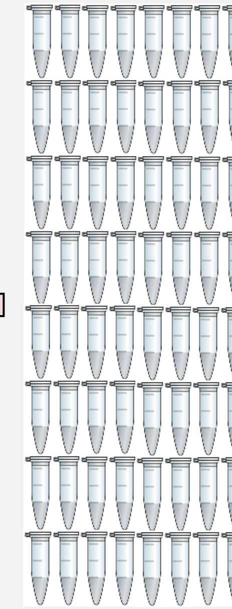


2. Refilling – *biophysical mechanisms*

P. nigra (black poplar)

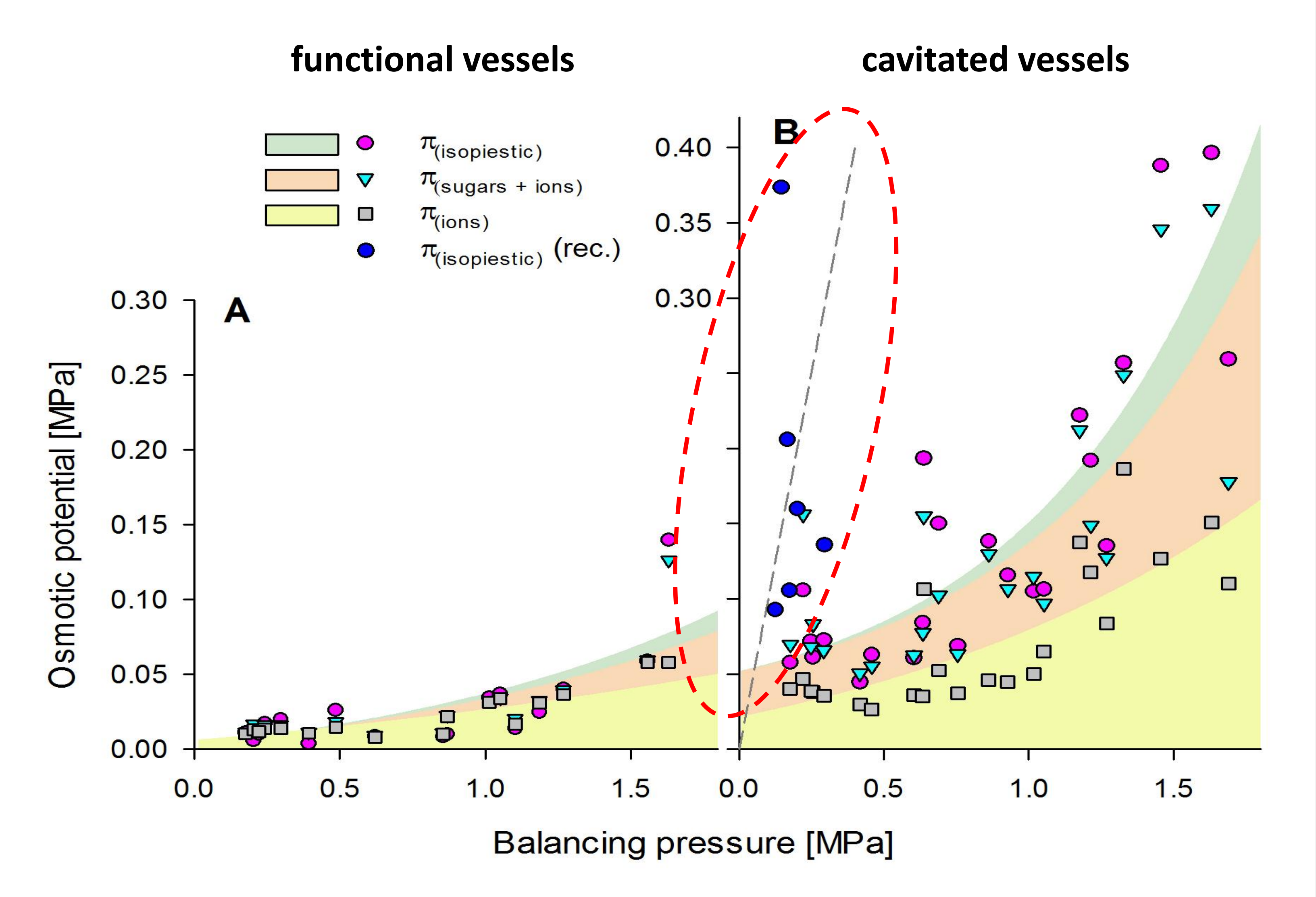
Francesca Secchi





Secret formula for water collection

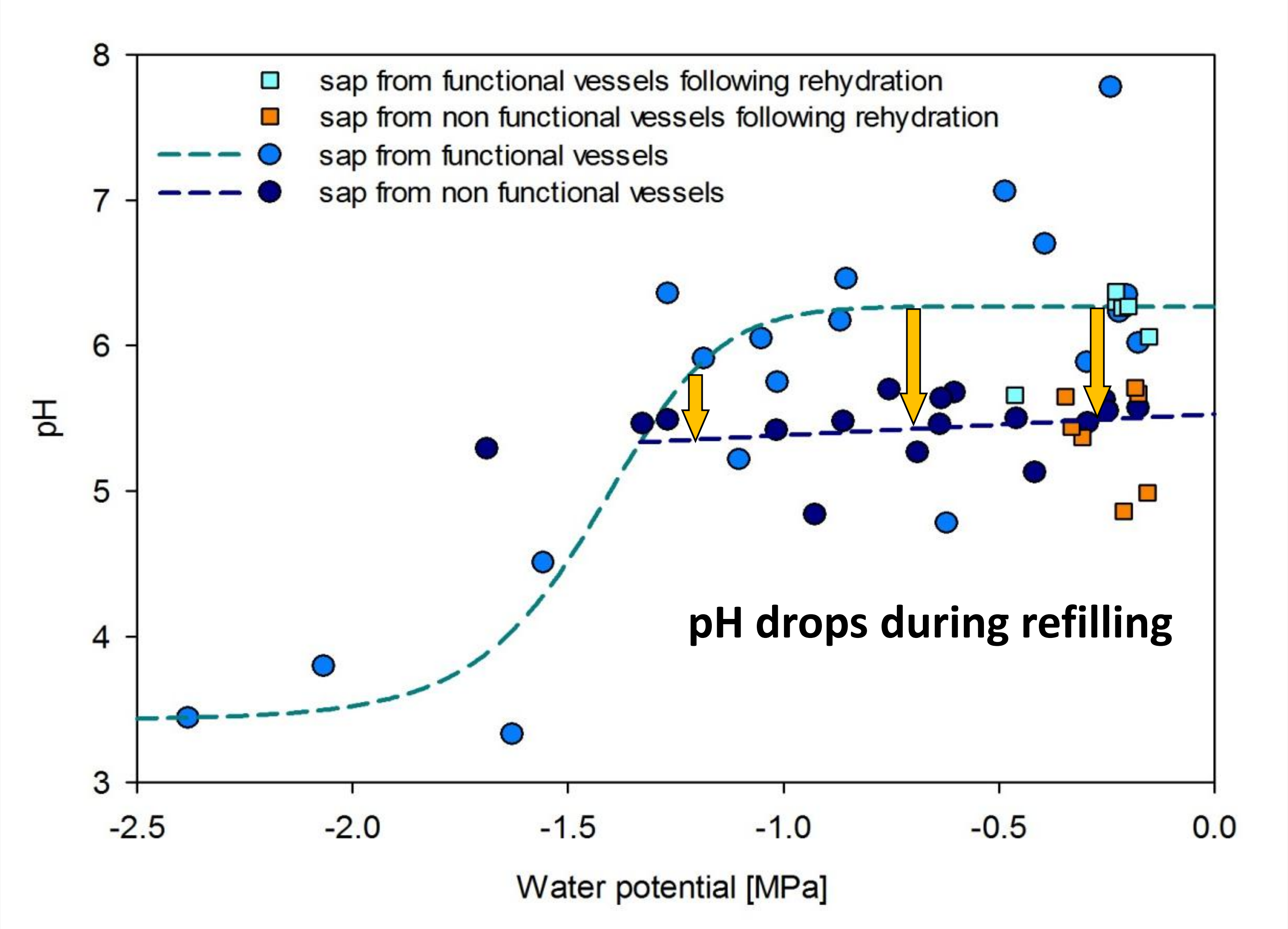
2. Refilling – biophysical mechanisms



- **osmolarity balances stress in rehydrated plant**

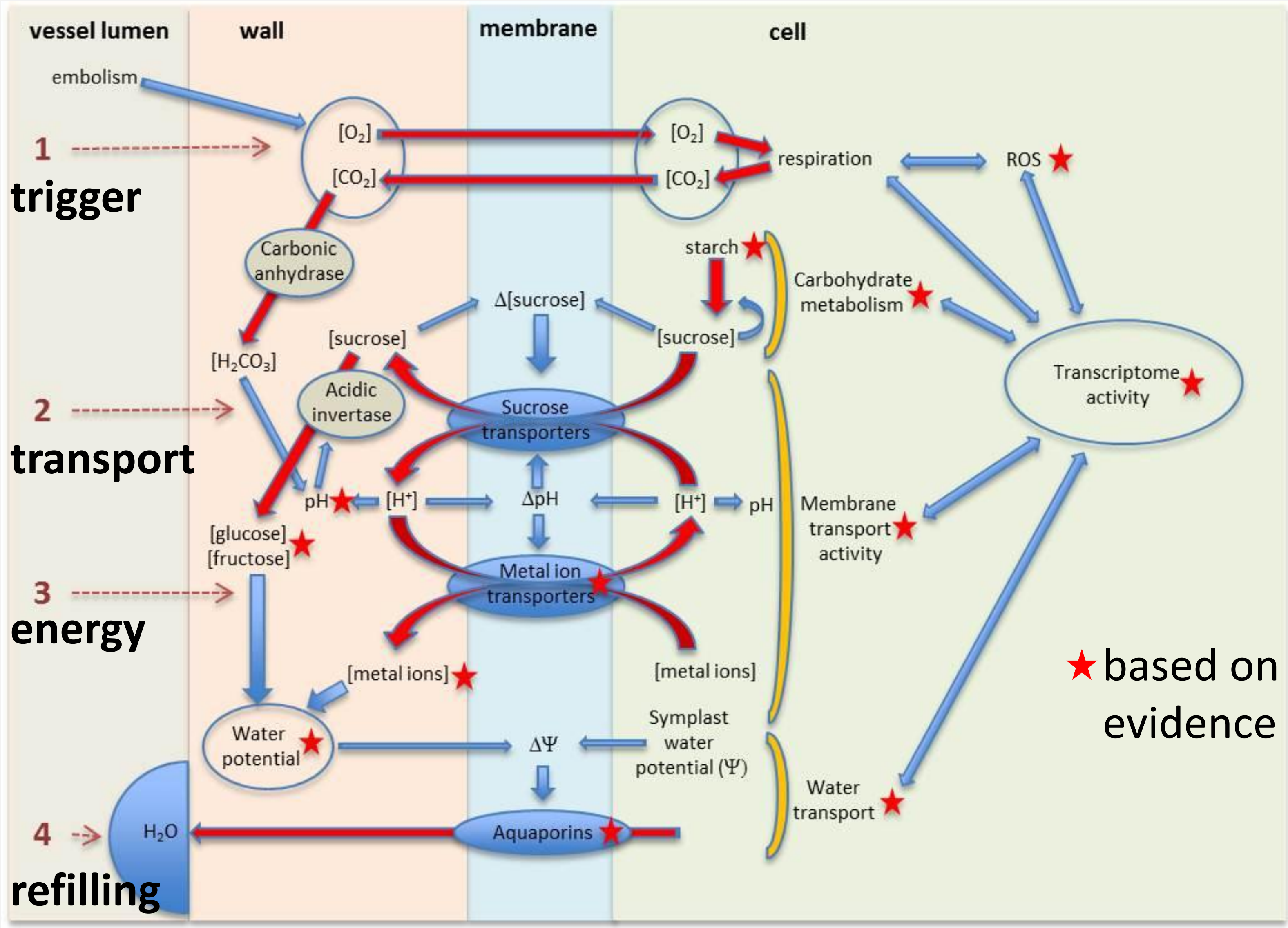
(Secchi & Zwieniecki, Plant Physio, 2012)

2. Refilling – biophysical mechanisms



(Secchi & Zwieniecki, Plant Physio, 2012)

2. Refilling – *emerging picture*

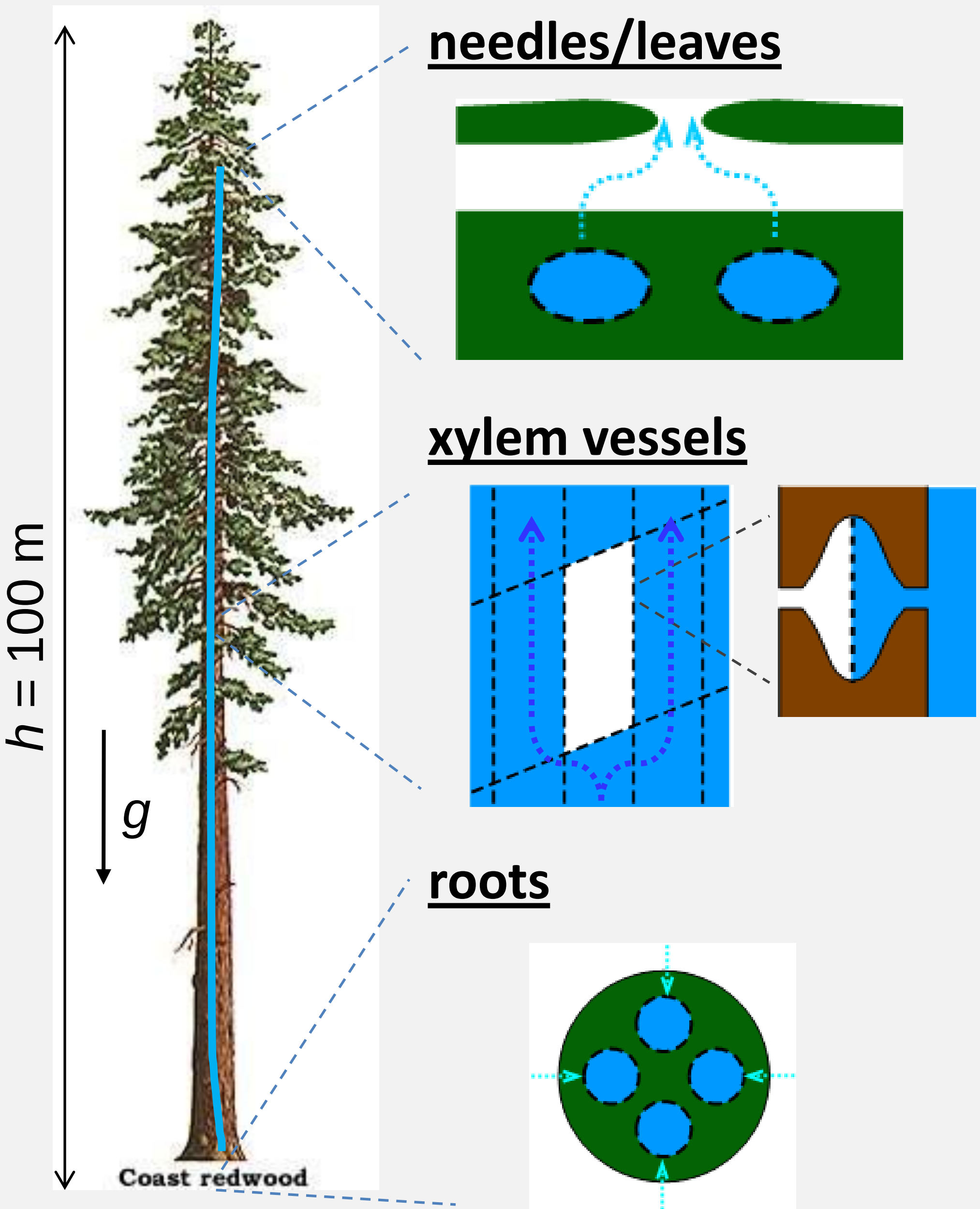


★ based on new evidence

⇒ **Not “dead wood”!**

(Secchi & Zwieniecki, Plant Physio, 2012)

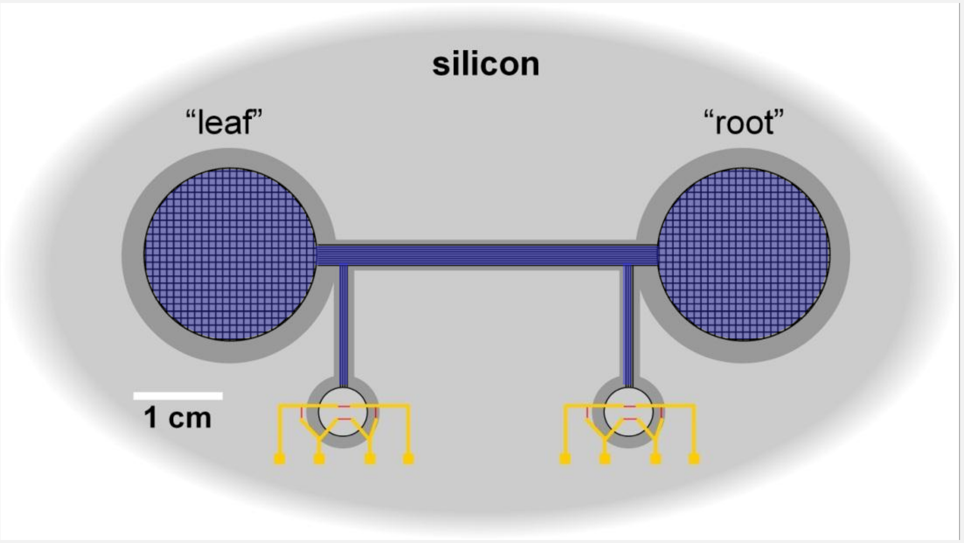
Synthetic tree – challenges



- **Material multifunctionality:**
  - high modulus
  - high thermal conductivity
  - integrated *nano-scale* and scale porosity
- **Integrated analysis:**
  - pressure, temperature, fluxes
- **Management of metastability:**
  - isolating cavitation (boiling) events
  - repairing cavitated zones
- **Fundamental understanding:**
  - transport and thermodynamics of liquids at NP

Synthetic tree – version 2.0

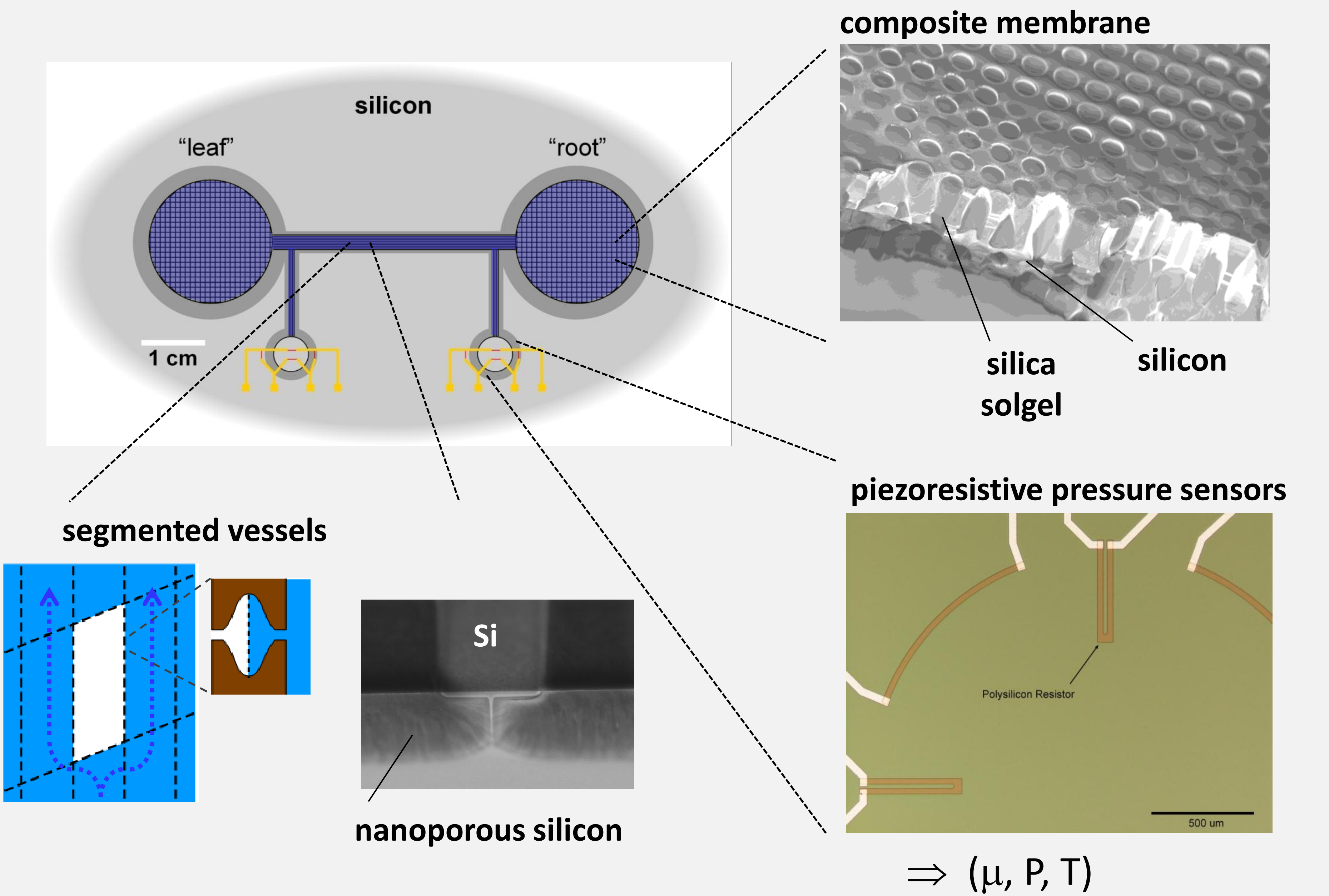
- **Wicks for negative pressure heat pipes**



- **Silicon MEMS platform**
  - → mechanical + thermal properties
  - → integration of sensors (pressure, temperature, flux)

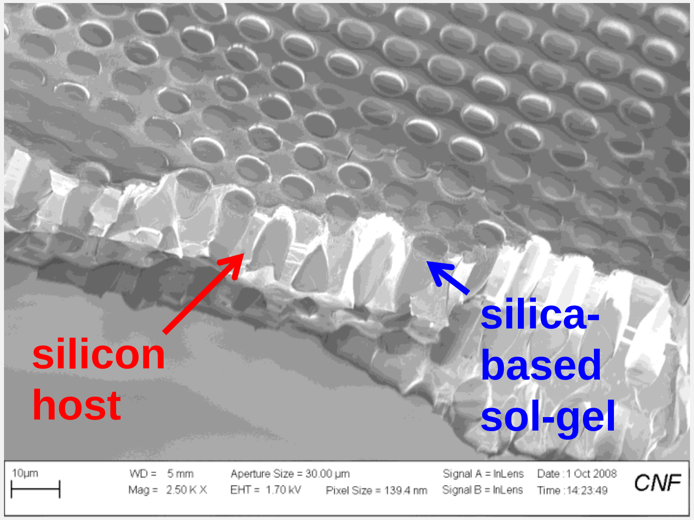
- **Composite structures**
  - → selective porosity
  - → large stresses/large fluxes
  - → failure isolation

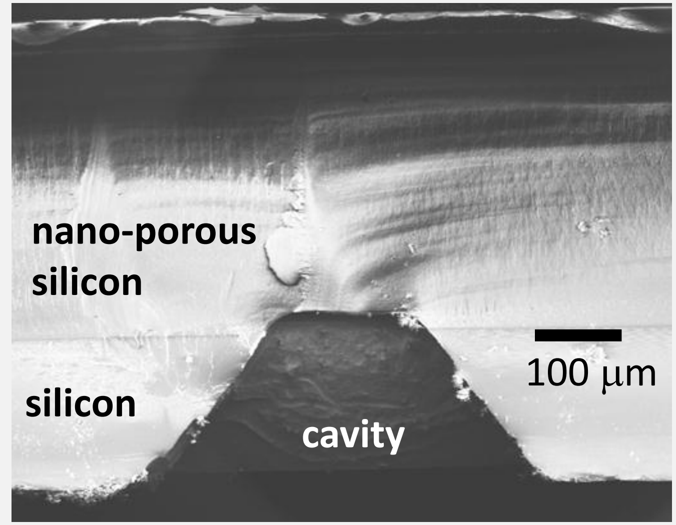
Synthetic tree – version 2.0

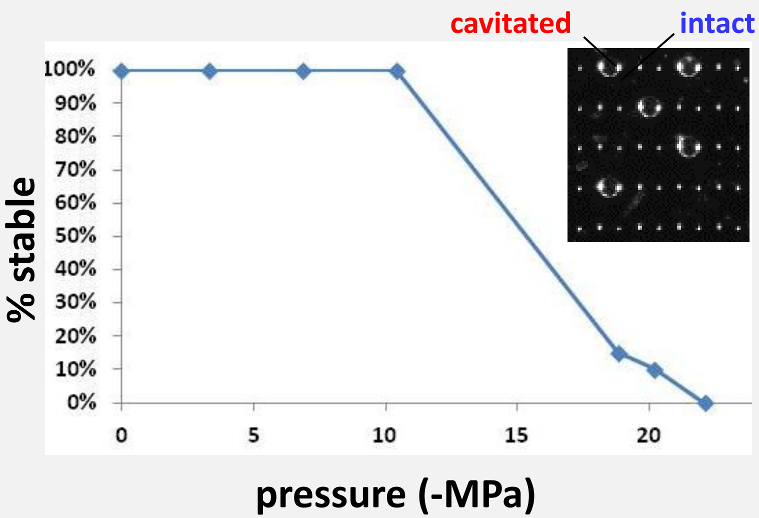


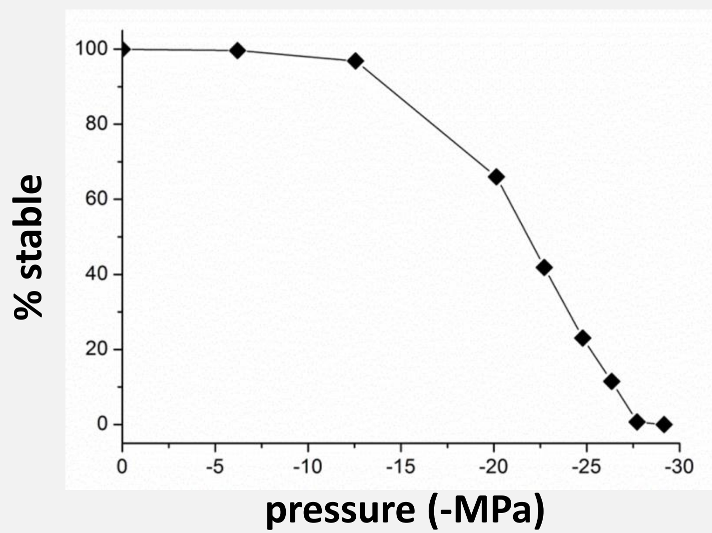
Synthetic tree – root/leaf membranes:

root/leaf membranes:



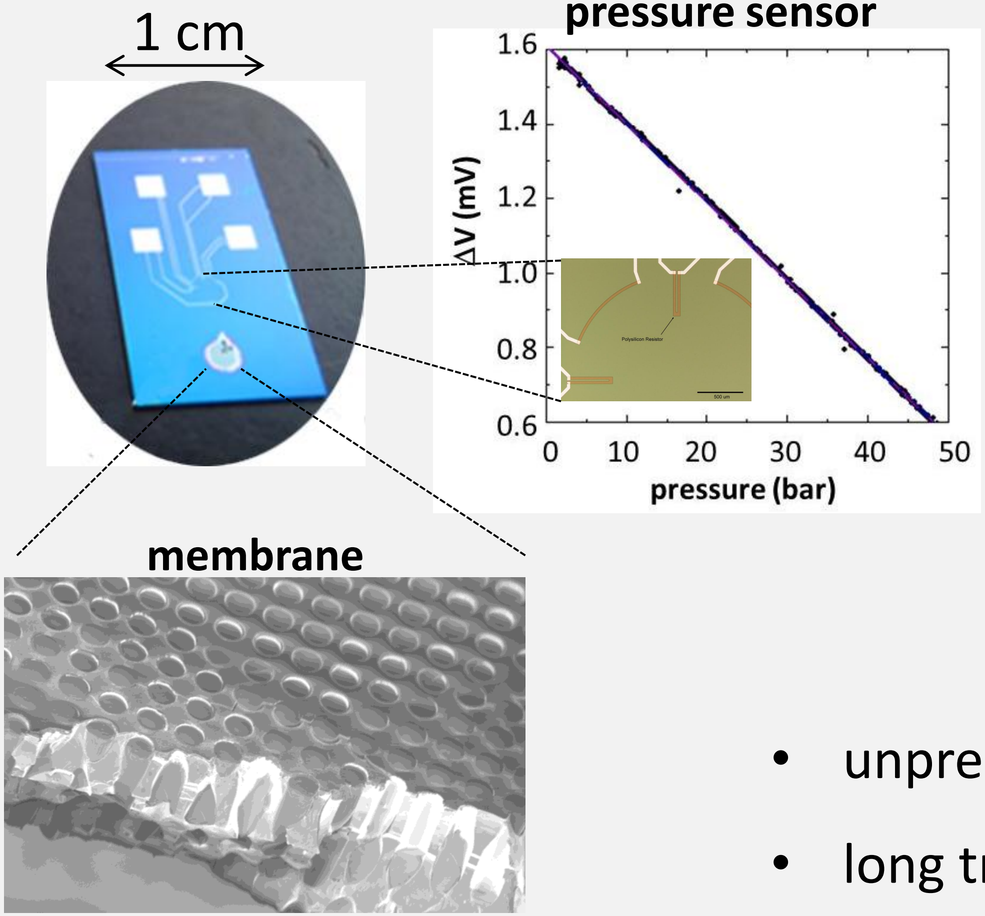


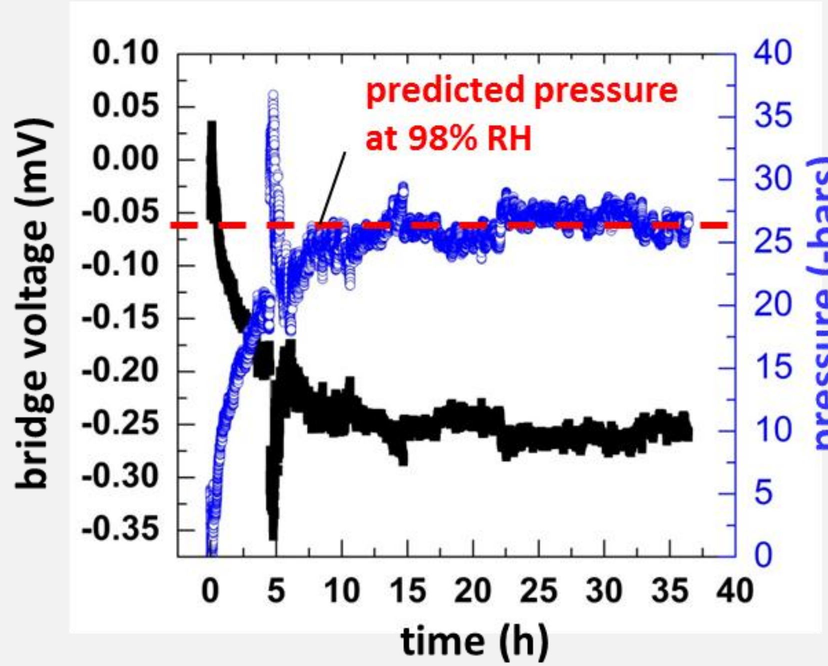




⇒ 100% stability to -100 bars

Synthetic tree – integration

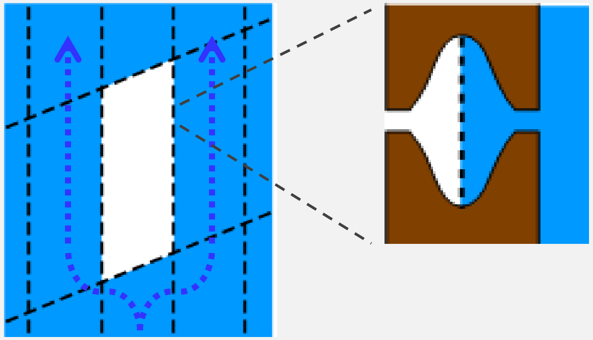


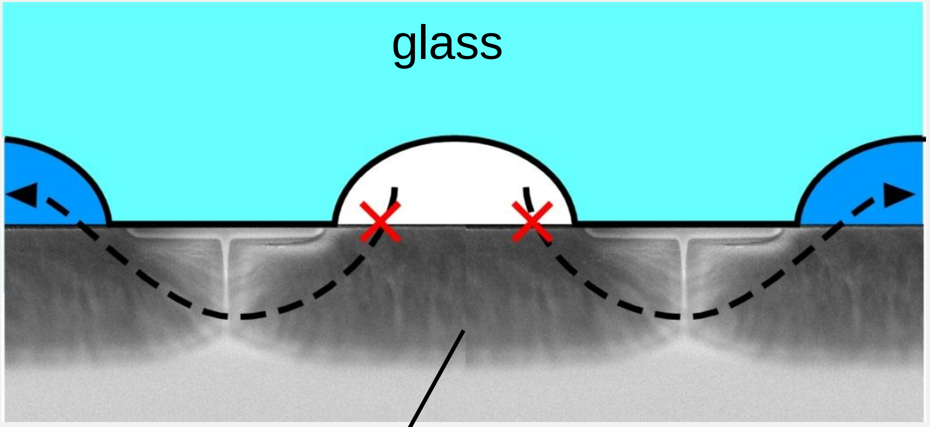


- unprecedented range
- long transients…
- embedding?

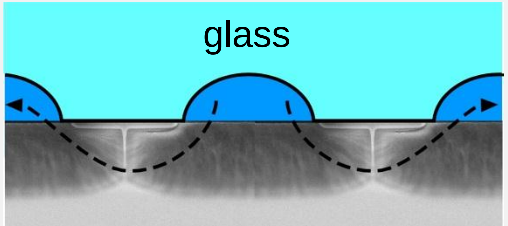
Synthetic trees – segmented xylem

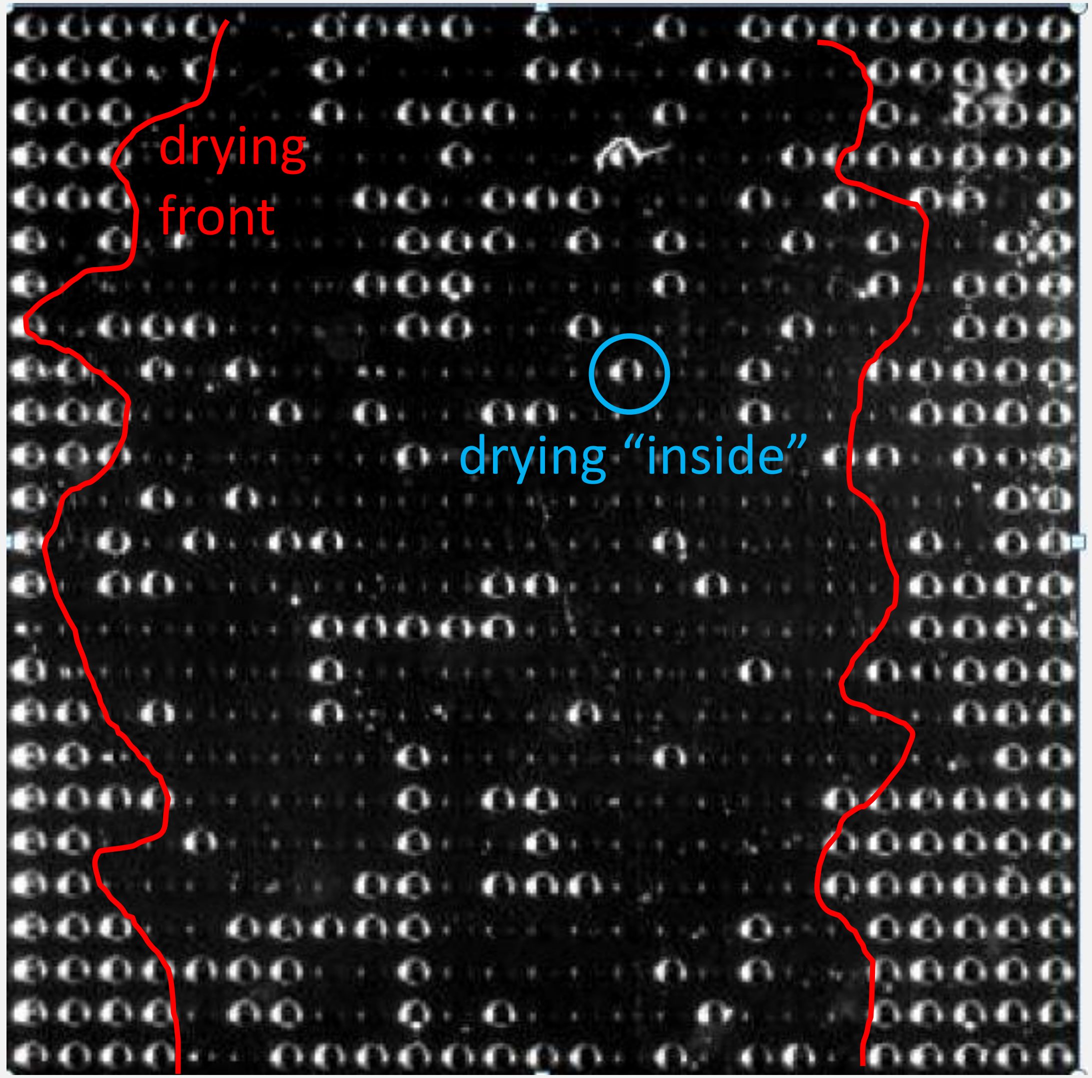
segmented vessels





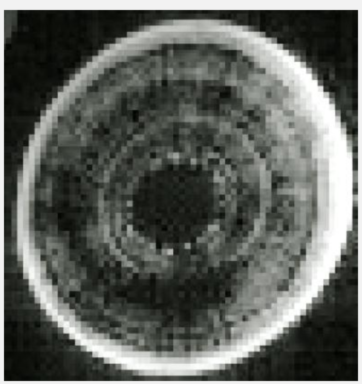
Synthetic trees – *segmented xylem*





drying
(a_{atm} = 0.73)

drying
(a_{atm} = 0.73

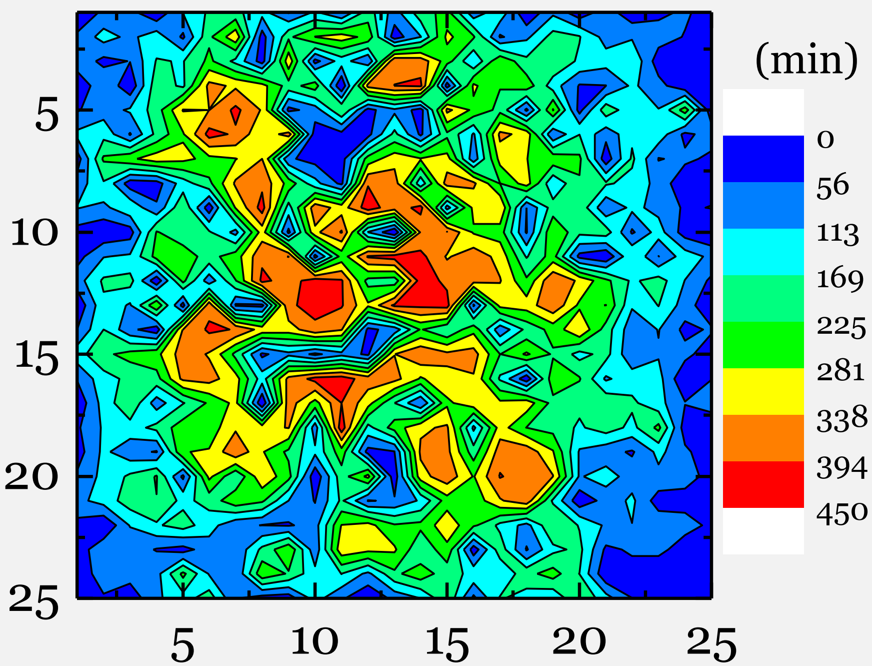


1 mm

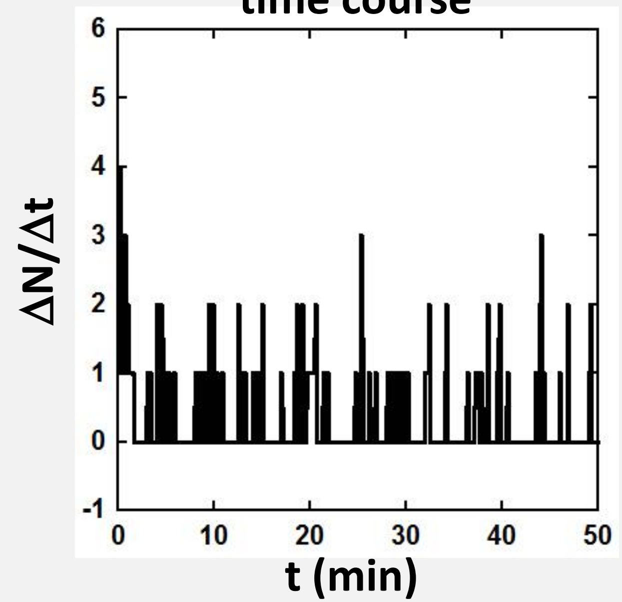
- **Spatially isolated cavitation events**

Synthetic trees – segmented xylem

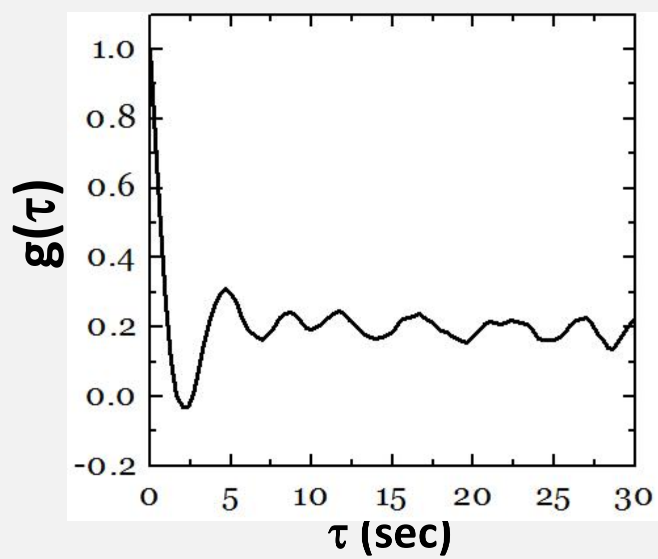
time to cavitation



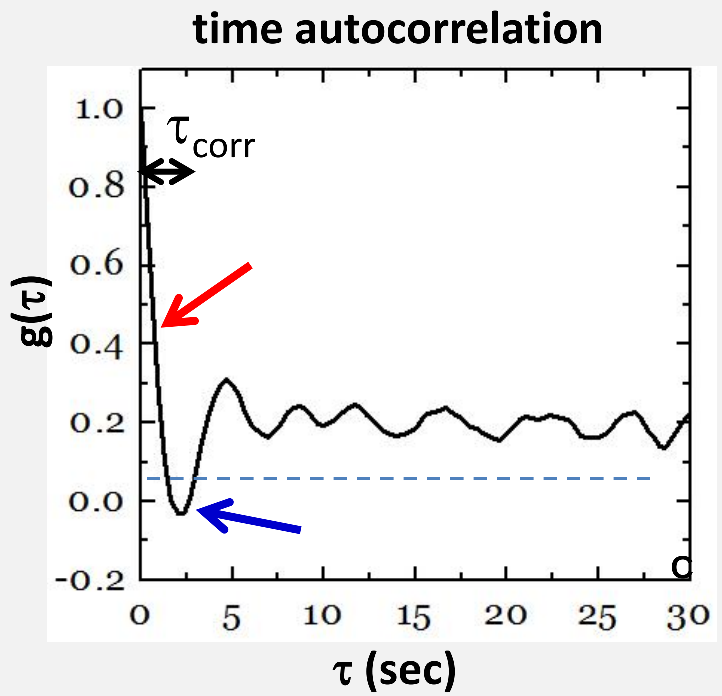
time course

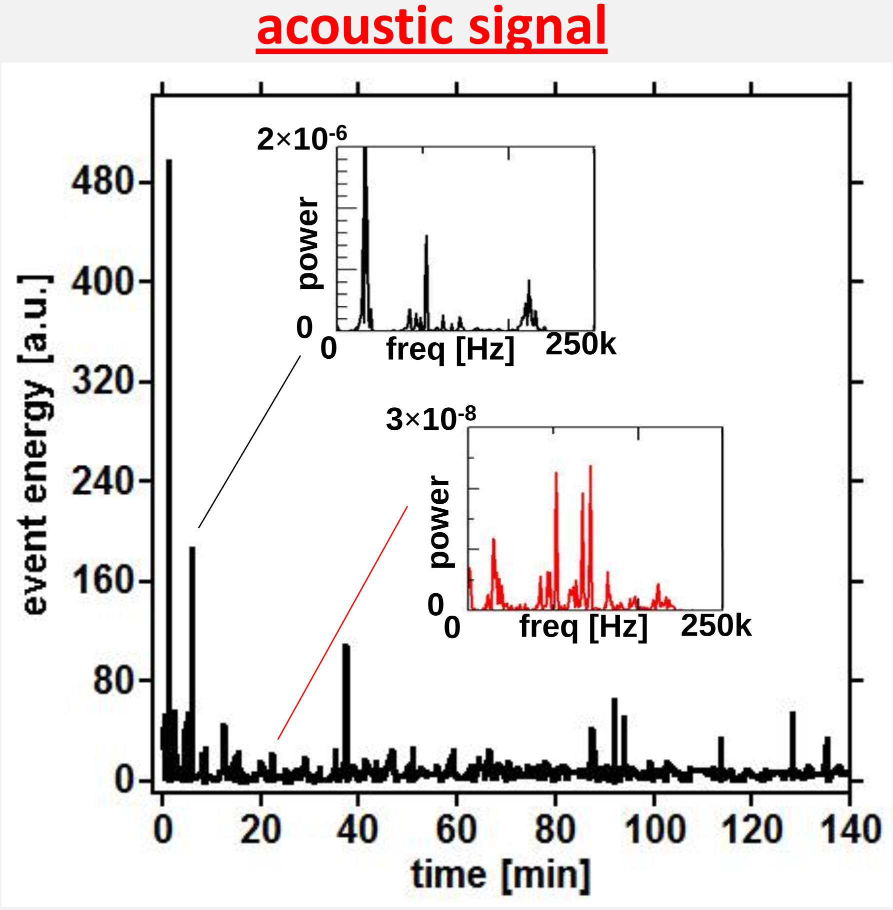


time autocorrelation



Synthetic trees – segmented xylem

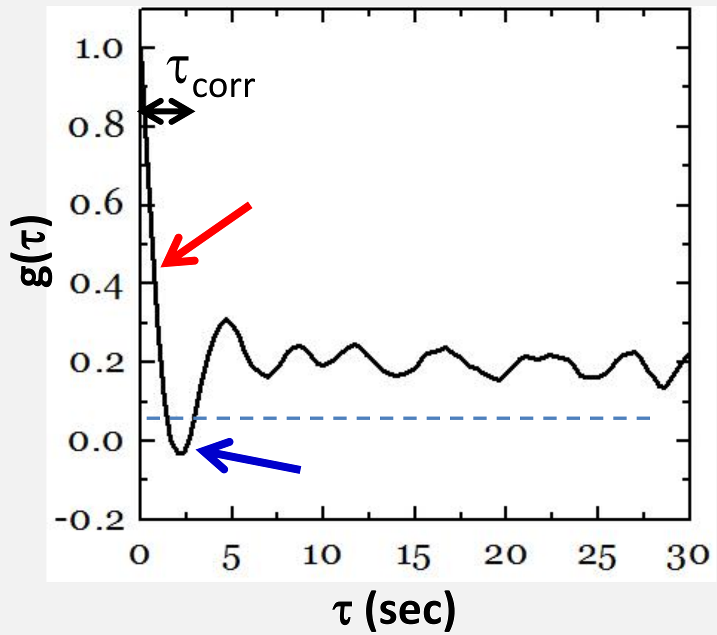




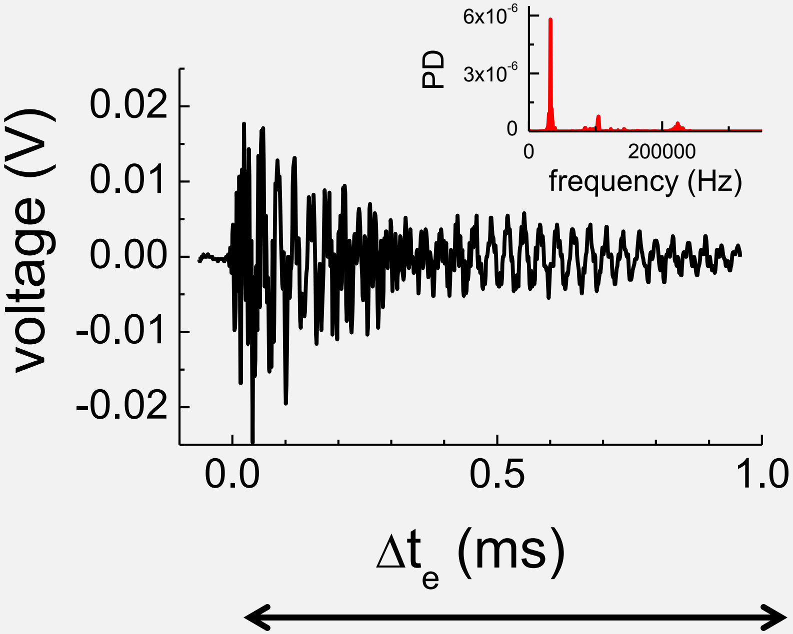
- acoustic triggering?
- hydraulic suppression?

Synthetic trees – segmented xylem

time autocorrelation



acoustic signal

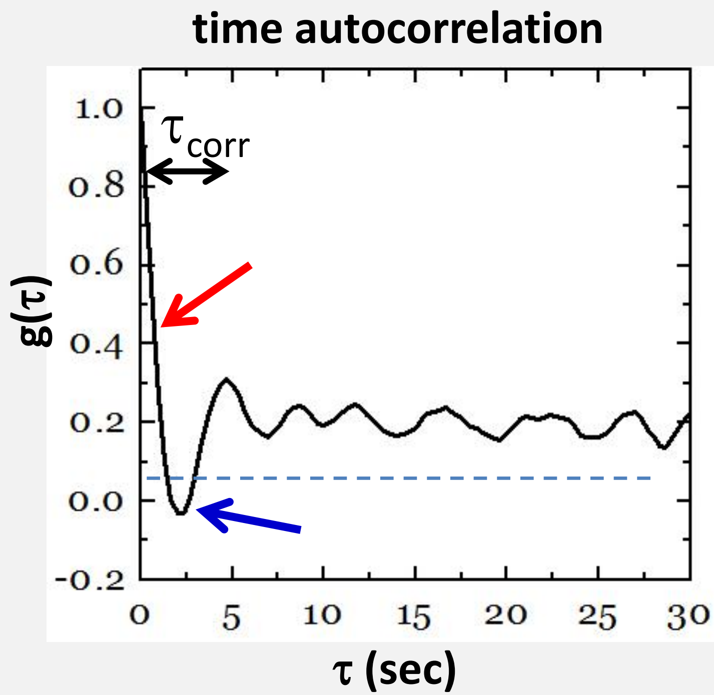


τ_{acoust} = 1 ms << τ_{corr}

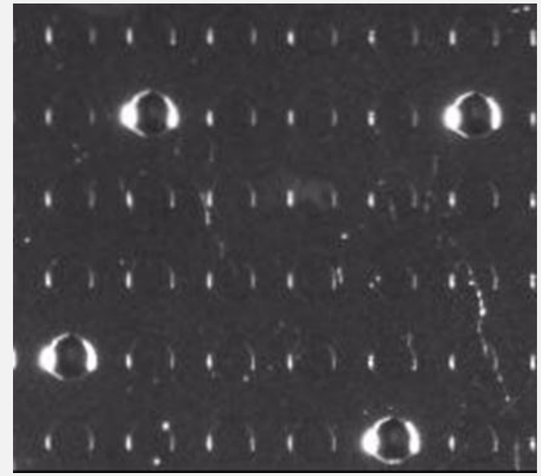
- ~~acoustic triggering?~~
- hydraulic suppression?

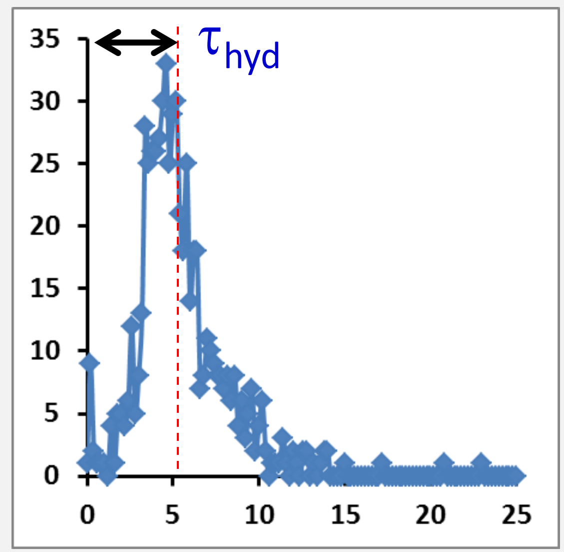
- **Acoustic signals, but not triggering additional events.**
- **But, acoustic signatures = opportunity for autonomic response.**

Synthetic tree – segmented xylem



hydraulic suppression





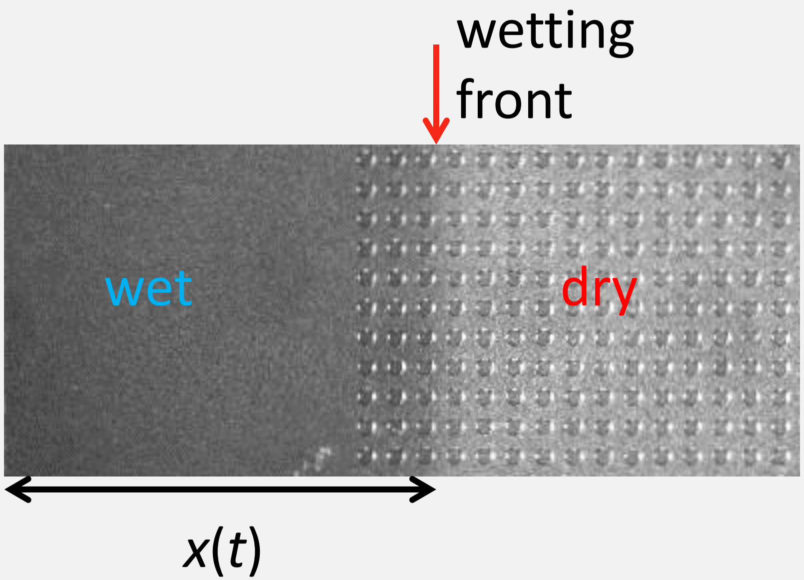
τ_{hyd} = 5.3 min $\cong \tau_{corr}$

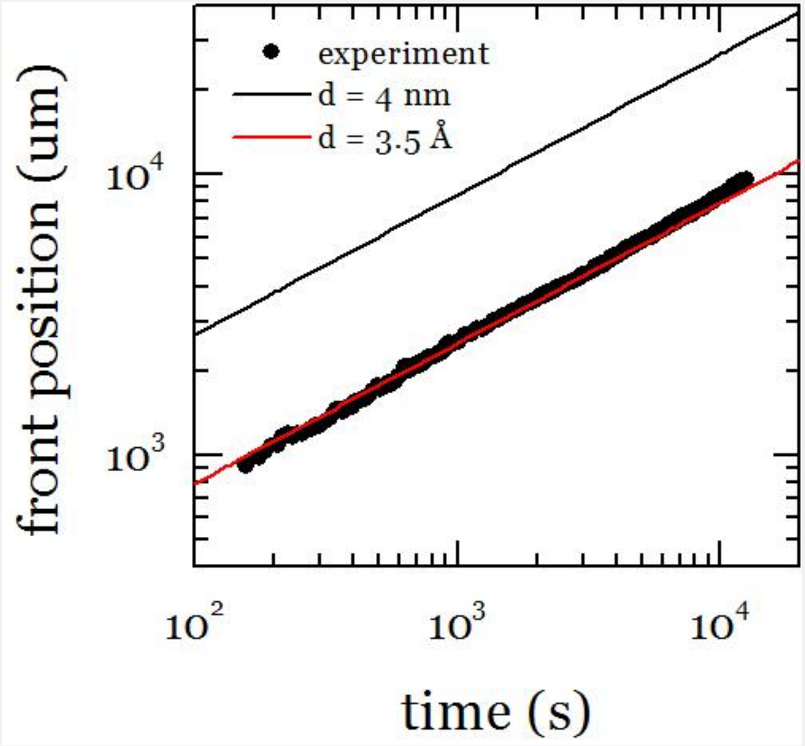
- ~~acoustic triggering?~~
- hydraulic suppression?

- **Drying proceeds in "avalanches" with suppression by re-saturation.**

Synthetic tree – segmented xylem

Physiology of "border pit membrane"?





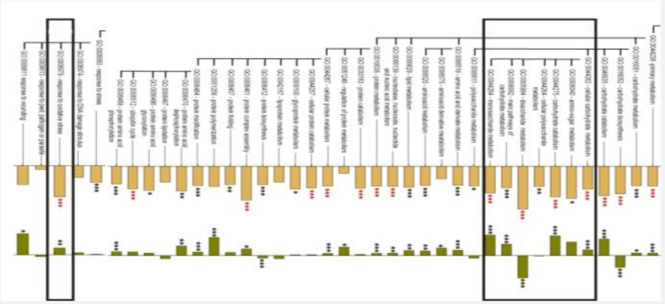
Washburn eqn. for capillary wetting:

$$x(t) = \sqrt{\frac{\gamma d_{pore} t}{4\eta}}$$

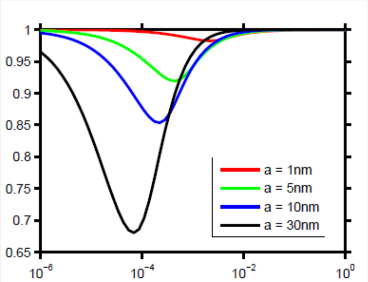
- d_{pore} = 0.35 nm
- consistent with τ_{hyd}

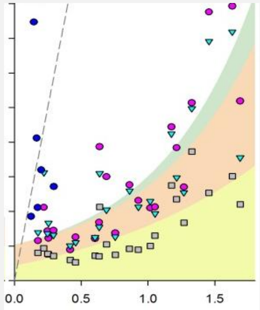
Conclusions

biomolecular insights

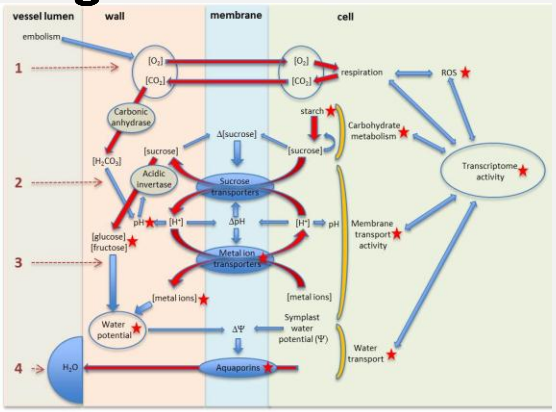


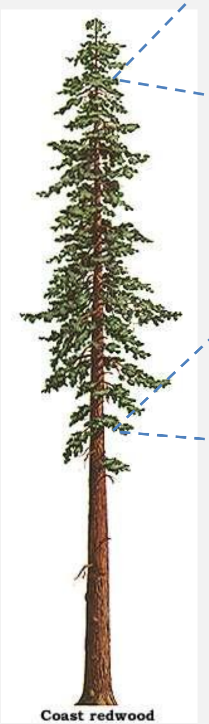
biophysical insights



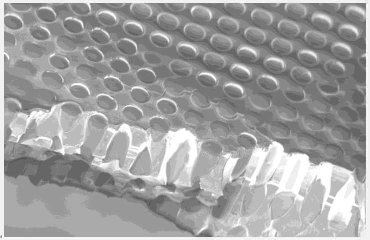


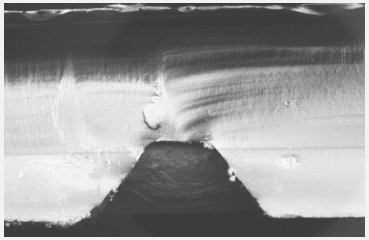
integrated understanding

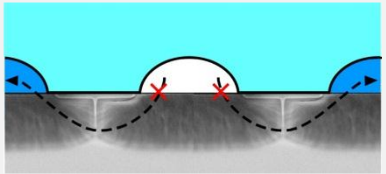




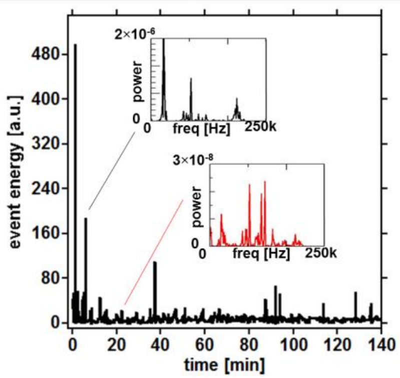
synthetic physiology







tools for integration



Acknowledgements

Grads:

- Erik Huber (MAE)
- I-Tzu Chen (CBE)
- Michael Santiago (MAE)
- Eugene Choi (CBE)
- Vinay Pagay (Hort.)
- Anthony Diaz (CBE)
- Pavithra Sundararajan (MAE)
- Vikram Singh (CBE)
- John Morgan (CBE)

Alumni:

- Tobias Wheeler (→ Caliper Inc.)
- Joseph Kirtland (→ Dordt College)
- Cecile Cottin-Bizonne (→ U. of Lyon)
- Mario Cabodi (→ Boston U.)
- Nakwon Choi (→ MIT/Novartis)
- Valerie Cross (→ Gore Inc.)
- Stephane Badaire (→ Michelin)
- Ying Zheng (→ UW Med)
- Amit Pharkya

Post-docs:

- Scott Verbridge
- Michael Craven
- David Sessoms
- Rachel Liang

Collaborators

- Frederic Caupin (Lyon)
- Michelle Holbrook (Harvard)
- Maciej Zwieniecki (Harvard)
- Francesca Secchi (Harvard)
- Alan Lakso (Cornell)

Funding: